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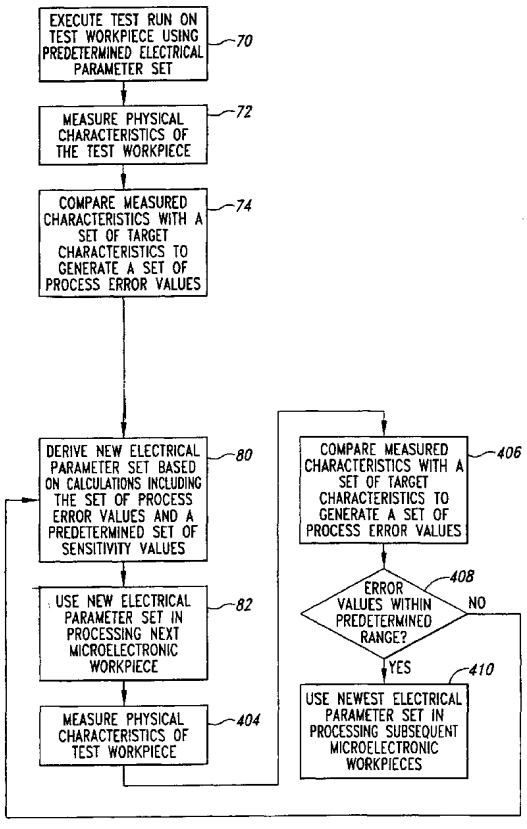
(54) Title: TUNING ELECTRODES USED IN A REACTOR FOR ELECTROCHEMICALLY PROCESSING A MICROELECTRONIC WORKPIECE



(57) Abstract: A facility for selecting and refining electrical parameters for processing a microelectronic workpiece in a processing chamber is described. The facility initially configures the electrical parameters in accordance with either a mathematical model of the processing chamber or experimental data derived from operating the actual processing chamber. After a workpiece is processed with the initial parameter configuration, the results are measured and a sensitivity matrix based upon the mathematical model of the processing chamber is used to select new parameters that correct for any deficiencies measured in the processing of the first workpiece. These parameters are then used in processing a second workpiece, which may be similarly measured, and the results used to further refine the parameters. In some embodiments, the facility analyzes a profile of the seed layer applied to a workpiece, and determines and communicates to a material deposition tool a set of control parameters designed to deposit material on the workpiece in a manner that compensates for deficiencies in the seed layer.

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TUNING ELECTRODES USED IN A REACTOR FOR ELECTROCHEMICALLY PROCESSING A MICROELECTRONIC WORKPIECE

FIELD OF THE INVENTION

The present invention is directed to the field of automatic process control, and, more particularly, to the field of controlling a material deposition process.

BACKGROUND OF THE INVENTION

The fabrication of microelectronic components from a microelectronic workpiece, such as a semiconductor wafer substrate, polymer substrate, etc., involves a substantial number of processes. For purposes of the present application, a microelectronic workpiece is defined to include a workpiece formed from a substrate upon which microelectronic circuits or components, data storage elements or layers, and/or micro-mechanical elements are formed. There are a number of different processing operations performed on the microelectronic workpiece to fabricate the microelectronic component(s). Such operations include, for example, material deposition, patterning, doping, chemical mechanical polishing, electropolishing, and heat treatment.

Material deposition processing involves depositing or otherwise forming thin layers of material on the surface of the microelectronic workpiece. Patterning provides selective deposition of a thin layer and/or removal of selected portions of these added layers. Doping of the semiconductor wafer, or similar microelectronic workpiece, is the process of adding impurities known as "dopants" to selected portions of the wafer to alter the electrical characteristics of the substrate material. Heat treatment of the microelectronic workpiece involves heating and/or

cooling the workpiece to achieve specific process results. Chemical mechanical polishing involves the removal of material through a combined chemical/mechanical process while electropolishing involves the removal of material from a workpiece surface using electrochemical reactions.

Numerous processing devices, known as processing "tools," have been developed to implement one or more of the foregoing processing operations. These tools take on different configurations depending on the type of workpiece used in the fabrication process and the process or processes executed by the tool. One tool configuration, known as the LT-210C™ processing tool and available from Semitool, Inc., of Kalispell, Montana, includes a plurality of microelectronic workpiece processing stations that are serviced by one or more workpiece transfer robots. Several of the workpiece processing stations utilize a workpiece holder and a process bowl or container for implementing wet processing operations. Such wet processing operations include electroplating, etching, cleaning, electroless deposition, electropolishing, etc. In connection with the present invention, it is the electrochemical processing stations used in the LT-210C™ that are noteworthy. Such electrochemical processing stations perform the foregoing electroplating, electropolishing, anodization, etc., of the microelectronic workpiece. It will be recognized that the electrochemical processing system set forth herein is readily adapted to implement each of the foregoing electrochemical processes.

In accordance with one configuration of the LT-210C™ tool, the electrochemical processing stations include a workpiece holder and a process container that are disposed proximate one another. The workpiece holder and process container are operated to bring the microelectronic workpiece held by the workpiece holder into contact with an electrochemical processing fluid disposed in the process container. When the microelectronic workpiece is positioned in this manner, the workpiece holder and process container form a processing chamber that may be open, enclosed, or substantially enclosed.

Electroplating and other electrochemical processes have become important in the production of semiconductor integrated circuits and other

microelectronic devices from microelectronic workpieces. For example, electroplating is often used in the formation of one or more metal layers on the workpiece. These metal layers are often used to electrically interconnect the various devices of the integrated circuit. Further, the structures formed from the metal layers may constitute microelectronic devices such as read/write heads, etc.

Electroplated metals typically include copper, nickel, gold, platinum, solder, nickel-iron, etc. Electroplating is generally effected by initial formation of a seed layer on the microelectronic workpiece in the form of a very thin layer of metal, whereby the surface of the microelectronic workpiece is rendered electrically conductive. This electro-conductivity permits subsequent formation of a blanket or patterned layer of the desired metal by electroplating. Subsequent processing, such as chemical mechanical planarization, may be used to remove unwanted portions of the patterned or metal blanket layer formed during electroplating, resulting in the formation of the desired metallized structure.

Electropolishing of metals at the surface of a workpiece involves the removal of at least some of the metal using an electrochemical process. The electrochemical process is effectively the reverse of the electroplating reaction and is often carried out using the same or similar reactors as electroplating.

Anodization typically involves oxidizing a thin-film layer at the surface of the workpiece. For example, it may be desirable to selectively oxidize certain portions of a metal layer, such as a Cu layer, to facilitate subsequent removal of the selected portions in a solution that etches the oxidized material faster than the non-oxidized material. Further, anodization may be used to deposit certain materials, such as perovskite materials, onto the surface of the workpiece.

As the size of various microelectronic circuits and components decreases, there is a corresponding decrease in the manufacturing tolerances that must be met by the manufacturing tools. In connection with the present invention as described below, electrochemical processes must uniformly process the surface of a given microelectronic workpiece. Further, the electrochemical process must meet workpiece-to-workpiece uniformity requirements.

Electrochemical processes may be conducted in reaction chambers having either a single electrode or multiple electrodes. Where a single-electrode reaction chamber is used, improving the level uniformity achieved by the process often involves manual trial-and-error modifications to the hardware configuration of the reaction chamber. For example, operators of the process may experiment with repositioning or reorienting the electrode, the workpiece, or a baffle separating the electrode from the workpiece, or may modify aspects of a fluid flow within the reaction chamber in attempts to improve the level uniformity achieved by the process.

In a multiple-electrode reaction chamber, two or more electrodes are arranged in some pattern. Each of the electrodes is connected to an electrical power supply that provides the electrical power used to execute the electrochemical processing operations. Preferably, at least some of the electrodes are connected to different electrical nodes so that the electrical power provided to them by the power supply may be provided independent of the electrical power provided to other electrodes in the array.

Electrode arrays having a plurality of electrodes facilitate localized control of the electrical parameters used to electrochemically process the microelectronic workpiece. This localized control of the electrical parameters can be used to provide greater uniformity of the electrochemical processing across the surface of the microelectronic workpiece when compared to single electrode systems without necessitating hardware changes. However, determining the electrical parameters for each of the electrodes in the array to achieve the desired process uniformity can be problematic. Typically, the electrical parameter (*i.e.*, electrical current, voltage, etc.) for a given electrode in a given electrochemical process is determined experimentally using a manual trial and error approach. Using such a manual trial and error approach, however, can be very time-consuming. Further, the electrical parameters do not easily translate to other electrochemical processes. For example, a given set of electrical parameters used to electroplate a metal to a thickness X onto the surface of a microelectronic

workpiece cannot easily be used to derive the electrical parameters used to electroplate a metal to a thickness Y. Still further, the electrical parameters used to electroplate a desired film thickness X of a given metal (*e.g.*, copper) are generally not suitable for use in electroplating another metal (*e.g.*, platinum). Similar deficiencies in this trial and error approach are associated with other types of electrochemical processes (*i.e.*, anodization, electropolishing, etc.). Also, this manual trial and error approach often must be repeated in several common circumstances, such as when the thickness or level of uniformity of the seed layer changes, when the target plating thickness or profile changes, or when the plating rate changes.

In view of the foregoing, a system for electrochemically processing a microelectronic workpiece that can be used to automatically identify electrical parameters that cause a multiple electrode array to achieve a high level of uniformity for a wide range of electrochemical processing variables (*e.g.*, seed layer thicknesses, seed layer types, electroplating materials, etc.) would have significant utility.

SUMMARY

In the following, a facility for automatically identifying electrical parameters that produce a high level of uniformity in electrochemically processing a microelectronic workpiece is described. Embodiments of this facility are adapted to accommodate various electrochemical processes; reactor designs and conditions; plating materials and solutions; workpiece dimensions, materials, and conditions, and the nature and condition of existing coatings on the workpiece. Accordingly, use of the facility may typically result in substantial automation of electrochemical processing, even where a large number of variables in different dimensions are present. Such automation has the capacity to reduce the cost of skilled labor required to oversee a processing operation, as well as increase output quality and throughput. Additionally, use of the facility can both streamline and improve the process of designing new electroplating reactors.

In one exemplary embodiment, the facility selects and refines electrical parameters for processing a microelectronic workpiece in a processing chamber. The facility initially configures the electrical parameters in accordance with either a mathematical model of the processing chamber or experimental data derived from operating the actual processing chamber. After a workpiece is processed with the initial parameter configuration, the results are measured and a sensitivity matrix based upon the mathematical model of the processing chamber is used to select new parameters that correct for any deficiencies measured in the processing of the first workpiece. These parameters are then used in processing a second workpiece, which may be similarly measured, and the results used to further refine the parameters.

In another exemplary embodiment, the facility utilizes a sensitivity matrix data structure. The sensitivity matrix data structure relates to a deposition chamber for depositing material on a workpiece. The deposition chamber has a number of deposition initiators, associated with each of which is a control parameter. For example, the deposition chamber may have deposition initiators that are electrodes, whose control parameters are electrical current levels or other control parameters. The data structure contains a number of quantitative entries, each of which predicts, for a given change in the control parameter associated with a given deposition initiator, the expected change in deposited material thickness at a given radius. The contents of this data structure may be used to determine revised deposition initiator parameters for better conforming deposited material thicknesses to a target profile for deposited material thicknesses.

In another exemplary embodiment, the facility utilizes a material deposition process data structure, which contains a set of parameter values used in a material deposition process. These parameters have been generated by adjusting an earlier-used set of parameters to resolve differences between measurements of a workpiece deposited using the earlier-used set of parameters in a target deposition profile specified for the deposition process. The contents of this data structure may

be used to deposit an additional workpiece in great conformance with the specified deposition profile.

In another exemplary embodiment, the facility controls an electroplating process having multiple steps, which is performed in an electroplating chamber having a number of electrodes. For each electrode, the facility determines the net plating charge delivered through the electrode during a first plating cycle to plate a first workpiece. This is accomplished by summing the plating charges delivered through the electrode in each step of the process. The facility then compares a plating profile achieved in plating the first workpiece to a target plating profile. In such comparison, the facility identifies deviations between the achieved plating profile and the target plating profile. The facility determines new net plating charges for each electrode selected to reduce the identified deviations in the second workpiece. For each of these new net plating charges, the facility distributes the new net plating charge across the steps of the process, and uses the distributed new net plating charges to determine a current for each electrode for each step of the process. A second plating cycle may then be conducted to plate a second workpiece using the currents determined for each electrode for each step.

In another exemplary embodiment, the facility evaluates a design for an electroplating reactor. The facility first applies a mathematical model embodying the reactor design to a set of initial electrode current to determine a first resulting plating profile. The facility compares the first resulting plating profile to a target plating profile to obtain a first difference. The facility then applies a sensitivity technique to identify a set of revised electrode currents, and applies the mathematical model to the set of revised electrode currents to determine a second resulting plating profile. The facility compares the second resulting plating profile to the target plating profile to obtain a second difference, and evaluates the design based on the obtained second difference.

In another exemplary embodiment, the facility is embodied in an apparatus for selecting parameters for use in controlling operation of a deposition chamber to deposit material on a selected wafer in a way that optimizes conformity

with a specified deposition pattern. The apparatus includes a measurement receiving subsystem that receives the following measurements: pre-deposition thicknesses of the selected wafer before material is deposited on the wafer; post-deposition thicknesses of an already-deposited wafer after material is deposited on the already-deposited wafer; and pre-deposition thicknesses of the already-deposited wafer before material is deposited on the wafer. The apparatus further includes a parameter selection subsystem that selects the parameters to be used to deposit material on the selected wafer based on the specified deposition pattern, the pre-deposition thicknesses of the selected wafer, the pre-deposition thicknesses of the already-deposited wafer, parameters used for depositing material on the already-deposited wafer, and the post-deposition thicknesses of the already-deposited wafer.

In another exemplary embodiment, the facility electroplates a selected surface using a plurality of electrodes. The facility obtains a current specification set comprised of a plurality of current levels, each specified for a particular one of the plurality of electrodes. The current levels of the current specification set each represent a modification of current levels of a distinguished current specification set, modified in order to improve results produced by electroplating in accordance with the distinguished current specification set. For each electrode, the facility delivers the current level specified for the electrode by the current specification set to the electrode in order to electroplate the selected surface.

In another exemplary embodiment, the facility automatically configures parameters usable to control operation of a reaction chamber to electropolish a selected wafer in a way that optimizes conformity with a specified electropolishing pattern. The facility receives pre-polishing thicknesses of the selected wafer before the selected wafer is polished. The facility also receives post-polishing thicknesses of an already-polished wafer the already-polished wafer is polished. The facility further receives pre-polishing thicknesses of the already-polished wafer before the already-polished wafer is polished. The facility selects the parameters to polish the selected wafer based on the specified polishing pattern, the pre-polishing thicknesses of the selected wafer, the pre-polishing thicknesses of

the already-polished wafer, parameters used for polishing the already-polished wafer, and the post-polishing thicknesses of the already-polished wafer.

In another exemplary embodiment, the facility electroplates a microelectronic workpiece. The facility receives data representing a profile of a seed layer that has been applied to the workpiece, such as from a metrology station. The facility identifies deficiencies in the seed layer based upon the profile of the seed layer represented by the received data, and determines a set of control parameters for plating the workpiece in a manner that compensates for the identified deficiencies in the seed layer. The facility communicates this determined set of control parameters to a plating tool for use in plating the workpiece.

In another exemplary embodiment, the facility is embodied in a processing container for electrochemically processing a microelectronic workpiece. The processing container includes a principal fluid flow chamber. At different elevations in the principal fluid flow chamber, a number of concentric anodes are disposed so as to place the concentric anodes at different distances from a microelectronic workpiece under process. The processing container further includes a controller that is configured to deliver through each of the concentric anodes a current that is both (a) based upon a current delivery through the concentric anode to process an earlier-processed microelectronic workpiece and (b) selected to produce a more uniform processing of the workpiece under process then the processing of the earlier-processed microelectronic workpiece.

In another exemplary embodiment, the facility electroplates the material on a microelectronic workpiece. The facility introduces at least one surface of the microelectronic workpiece into an electroplating bath. The facility provides a plurality of anodes in the electroplating bath, spaced at different distances from the surface of the microelectronic workpiece that is to be electroplated. For each of the anodes, the facility induces an electrical current between the anode and the surface of the microelectronic workpiece. The induced electrical current is (a) based on an electrical current induced between the anode and a previously electroplated microelectronic workpiece and (b) selected to

improve on an electroplating result achieved for the previously electroplated microelectronic workpiece.

In a further exemplary embodiment, the facility performs a sensitivity analysis of the electroplating that is a basis for selecting the induced electric currents.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a process schematic diagram showing inputs and outputs of the optimizer.

Figure 2 is a process schematic diagram showing a branched correction system utilized by some embodiments of the optimizer.

Figure 3 is schematic block diagram of an electrochemical processing system constructed in accordance with one embodiment of the optimizer.

Figure 4 is a flowchart illustrating one manner in which the optimizer of Figure 3 can use a predetermined set of sensitivity values to generate a more accurate electrical parameter set for use in meeting targeted physical characteristics in the processing of a microelectronic workpiece.

Figure 5 is a graph of a sample Jacobian sensitivity matrix for a multiple-electrode reaction chamber.

Figure 6 is a spreadsheet diagram showing the new current outputs calculated from the inputs for the first optimization run.

Figure 7 is a spreadsheet diagram showing the new current outputs calculated from the inputs for the second optimization run.

DETAILED DESCRIPTION

A facility for automatically selecting and refining electrical parameters for processing a microelectronic workpiece ("the optimizer") is disclosed. In many embodiments, the optimizer determines process parameters affecting the processing of a round workpiece as a function of processing results at various radii on the workpiece. In some embodiments, the optimizer adjusts the

electrode currents for a multiple electrode electroplating chamber, such as multiple anode reaction chambers of the Paragon tool provided by Semitool, Inc. of Kalispell, Montana, in order to achieve a specified thickness profile (*i.e.*, flat, convex, concave, etc.) of a coating, such as a metal or other conductor, applied to a semiconductor wafer. The optimizer adjusts electrode currents for successive workpieces to compensate for changes in the thickness of the seed layer of the incoming workpiece (a source of feed forward control), and/or to correct for non-uniformities produced in prior wafers at the anode currents used to plate them (a source of feedback control). In this way, the optimizer is able to quickly achieve a high level of uniformity in the coating deposited on workpieces without substantial manual intervention.

The facility typically operates an electroplating chamber containing a principal fluid flow chamber, and a plurality of electrodes disposed in the principal fluid flow chamber. The electroplating chamber typically further contains a workpiece holder positioned to hold at least one surface of the microelectronic workpiece in contact with an electrochemical processing fluid in the principal fluid flow chamber, at least during electrochemical processing of the microelectronic workpiece. One or more electrical contacts are configured to contact the at least one surface of the microelectronic workpiece, and an electrical power supply is connected to the one or more electrical contacts and to the plurality of electrodes. At least two of the plurality of electrodes are independently connected to the electrical power supply to facilitate independent supply of power thereto. The apparatus also includes a control system that is connected to the electrical power supply to control at least one electrical power parameter respectively associated with each of the independently connected electrodes. The control system sets the at least one electrical power parameter for a given one of the independently connected electrodes based on one or more user input parameters and a plurality of predetermined sensitivity values; wherein the sensitivity values correspond to process perturbations resulting from perturbations of the electrical power parameter for the given one of the independently connected electrodes.

For example, although the present invention is described in the context of electrochemical processing of the microelectronic workpiece, the teachings herein can also be extended to other types of microelectronic workpiece processing. In effect, the teachings herein can be extended to other microelectronic workpiece processing systems that have individually controlled processing elements that are responsive to control parameters and that have interdependent effects on a physical characteristic of the microelectronic workpiece that is processed using the elements. Such systems may employ sensitivity tables or matrices as set forth herein and use them in calculations with one or more input parameters sets to arrive at control parameter values that accurately result in the targeted physical characteristic of the microelectronic workpiece.

Figure 1 is a process schematic diagram showing inputs and outputs of the optimizer. Figure 1 shows that the optimizer 140 uses up to three sources of input: baseline currents 110, seed change 120, and thickness error 130. The baseline currents 110 are the anode currents used to plate the previous wafer or another set of currents for which plating thickness results are known. For the first workpiece in a sequence of workpieces, the baseline currents used to plate the wafer are typically specified by a source other than the optimizer. For example, they may be specified by a recipe used to plate the wafers, or may be manually determined.

The seed change 120 is the difference between the thickness of the seed layer of the incoming wafer 121 and the thickness of the seed layer of the previous plated wafer 122. The seed change input 120 is said to be a source of feed-forward control in the optimizer, in that it incorporates information about the upcoming plating cycle, as it reflects the measurement the wafer to be plated in the upcoming plating cycle. Thickness error 130 is the difference in thickness between the previous plated wafer 132 and the target thickness profile 131 specified for the upcoming plating cycle. The thickness error 130 is said to be a source of feedback control, because it incorporates information from an earlier plating cycle, that is, the thickness of the wafer plated in the previous plating cycle.

Figure 1 further shows that the optimizer outputs new plating charges 150 for each electrode in the upcoming plating cycle, expressed in amp-minute units. The new plating charges output is combined with a recipe schedule and a current waveform 161 to generate the currents 162, in amps, to be delivered through each electrode at each point in the recipe schedule. These new currents are used by the plating process to plate a wafer in the next plating cycle. In embodiments in which different types of power supplies are used, other types of control parameters are generated by the optimizer for use in operating the power supply. For example, where a voltage control power supply is used, the control parameters generated by the optimizer are voltages, expressed in volts. The wafer so plated is then subjected to post-plating metrology to measure its plated thickness 132.

While the optimizer is shown as receiving inputs and producing outputs at various points in the processing of these values, it will be understood by those in the art that the optimizer may be variously defined to include or exclude aspects of such processing. For example, while Figure 1 shows the generation of seed change from baseline wafer seed thickness and seed layer thickness outside the optimizer, it is contemplated that such generation may alternatively be performed within the optimizer.

Figure 2 is a process schematic diagram showing a branched correction system utilized by some embodiments of the optimizer. The branched adjustment system utilizes two independently-engageable correction adjustments, a feedback adjustment (230, 240, 272) due to thickness errors and a feed forward adjustment (220, 240, 271) due to incoming seed layer thickness variation. When the anode currents produce an acceptable uniformity, the feedback loop may be disengaged from the transformation of baseline currents 210 to new currents 280. The feed forward compensation may be disengaged in situations where the seed layer variations are not expected to affect thickness uniformity. For example, after the first wafer of a similar batch is corrected for, the feed-forward compensation may be disengaged and the corrections may be applied to each sequential wafer in the batch.

Figure 3 is schematic block diagram of an electrochemical processing system constructed in accordance with one embodiment of the optimizer. Figure 3 shows a reactor assembly 20 for electrochemically processing a microelectronic workpiece 25, such as a semiconductor wafer, that can be used in connection with the present invention. Generally stated, an embodiment of the reactor assembly 20 includes a reactor head 30 and a corresponding reactor base or container shown generally at 35. The reactor base 35 can be a bowl and cup assembly for containing a flow of an electrochemical processing solution. The reactor 20 of Figure 3 can be used to implement a variety of electrochemical processing operations such as electroplating, electropolishing, anodization, etc., as well as to implement a wide variety of other material deposition techniques. For purposes of the following discussion, aspects of the specific embodiment set forth herein will be described, without limitation, in the context of an electroplating process.

The reactor head 30 of the reactor assembly 20 can include a stationary assembly (not shown) and a rotor assembly (not shown). The rotor assembly may be configured to receive and carry an associated microelectronic workpiece 25, position the microelectronic workpiece in a process-side down orientation within reactor container 35, and to rotate or spin the workpiece. The reactor head 30 can also include one or more contacts 85 (shown schematically) that provide electroplating power to the surface of the microelectronic workpiece. In the illustrated embodiment, the contacts 85 are configured to contact a seed layer or other conductive material that is to be plated on the plating surface microelectronic workpiece 25. It will be recognized, however, that the contacts 85 can engage either the front side or the backside of the workpiece depending upon the appropriate conductive path between the contacts and the area that is to be plated. Suitable reactor heads 30 with contacts 85 are disclosed in U.S. Patent No. 6,080,291 and U.S. Application Nos. 09/386,803; 09/386,610; 09/386,197; 09/717,927; and 09/823,948, all of which are expressly incorporated herein in their entirety by reference.

The reactor head 30 can be carried by a lift/rotate apparatus that rotates the reactor head 30 from an upwardly-facing orientation in which it can receive the microelectronic workpiece to a downwardly facing orientation in which the plating surface of the microelectronic workpiece can contact the electroplating solution in reactor base 35. The lift/rotate apparatus can bring the workpiece 25 into contact with the electroplating solution either coplanar or at a given angle. A robotic system, which can include an end effector, is typically employed for loading/unloading the microelectronic workpiece 25 on the head 30. It will be recognized that other reactor assembly configurations may be used with the inventive aspects of the disclosed reactor chamber, the foregoing being merely illustrative.

The reactor base 35 can include an outer overflow container 37 and an interior processing container 39. A flow of electroplating fluid flows into the processing container 39 through an inlet 42 (arrow *I*). The electroplating fluid flows through the interior of the processing container 39 and overflows a weir 44 at the top of processing container 39 (arrow *F*). The fluid overflowing the weir 44 then passes through an overflow container 37 and exits the reactor 20 through an outlet 46 (arrow *O*). The fluid exiting the outlet 46 may be directed to a recirculation system, chemical replenishment system, disposal system, etc.

The reactor 20 also includes an electrode in the processing container 39 to contact the electrochemical processing fluid (*e.g.*, the electroplating fluid) as it flows through the reactor 20. In the embodiment of Figure 3, the reactor 20 includes an electrode assembly 50 having a base member 52 through which a plurality of fluid flow apertures 54 extend. The fluid flow apertures 54 assist in disbursing the electroplating fluid flow entering inlet 42 so that the flow of electroplating fluid at the surface of microelectronic workpiece 25 is less localized and has a desired radial distribution. The electrode assembly 50 also includes an electrode array 56 that can comprise a plurality of individual electrodes 58 supported by the base member 52. The electrode array 56 can have several configurations, including those in which electrodes are disposed at different

distances from the microelectronic workpiece. The particular physical configuration that is utilized in a given reactor can depend on the particular type and shape of the microelectronic workpiece 25. In the illustrated embodiment, the microelectronic workpiece 25 is a disk-shaped semiconductor wafer. Accordingly, the present inventors have found that the individual electrodes 58 may be formed as rings of different diameters and that they may be arranged concentrically in alignment with the center of microelectronic workpiece 25. It will be recognized, however, that grid arrays or other electrode array configurations may also be employed without departing from the scope of the present invention. One suitable configuration of the reactor base 35 and electrode array 56 is disclosed in USSN 09/804,696, filed March 12, 2001 (Attorney Docket No. 29195.8119US), while another suitable configuration is disclosed in USSN 09/804,697, filed March 12, 2001 (Attorney Docket No. 29195.8120US), both of which are hereby incorporated by reference.

When the reactor 20 electroplates at least one surface of microelectronic workpiece 25, the plating surface of the workpiece 25 functions as a cathode in the electrochemical reaction and the electrode array 56 functions as an anode. To this end, the plating surface of workpiece 25 is connected to a negative potential terminal of a power supply 60 through contacts 85 and the individual electrodes 58 of the electrode array 56 are connected to positive potential terminals of the supply 60. In the illustrated embodiment, each of the individual electrodes 58 is connected to a discrete terminal of the supply 60 so that the supply 60 may individually set and/or alter one or more electrical parameters, such as the current flow, associated with each of the individual electrodes 58. As such, each of the individual electrodes 58 of Figure 3 is an individually controllable electrode. It will be recognized, however, that one or more of the individual electrodes 58 of the electrode array 56 may be connected to a common node/terminal of the power supply 60. In such instances, the power supply 60 will alter the one or more electrical parameters of the commonly connected electrodes 58 concurrently, as opposed to individually, thereby effectively making the commonly connected

electrodes 58 a single, individually controllable electrode. As such, individually controllable electrodes can be physically distinct electrodes that are connected to discrete terminals of power supply 60 as well as physically distinct electrodes that are commonly connected to a single discrete terminal of power supply 60. The electrode array 56 preferably comprises at least two individually controllable electrodes.

The electrode array 56 and the power supply 60 facilitate localized control of the electrical parameters used to electrochemically process the microelectronic workpiece 25. This localized control of the electrical parameters can be used to enhance the uniformity of the electrochemical processing across the surface of the microelectronic workpiece when compared to a single electrode system. Unfortunately, determining the electrical parameters for each of the electrodes 58 in the array 56 to achieve the desired process uniformity can be difficult. The optimizer, however, simplifies and substantially automates the determination of the electrical parameters associated with each of the individually controllable electrodes. In particular, the optimizer determines a plurality of sensitivity values, either experimentally or through numerical simulation, and subsequently uses the sensitivity values to adjust the electrical parameters associated with each of the individually controllable electrodes. The sensitivity values may be placed in a table or may be in the form of a Jacobian matrix. This table/matrix holds information corresponding to process parameter changes (*i.e.*, thickness of the electroplated film) at various points on the workpiece 25 due to electrical parameter perturbations (*i.e.*, electrical current changes) to each of the individually controllable electrodes. This table/matrix is derived from data from a baseline workpiece plus data from separate runs with a perturbation of a controllable electrical parameter to each of the individually controllable electrode.

The optimizer typically executes in a control system 65 that is connected to the power supply 60 in order to supply current values for a plating cycle. The control system 65 can take a variety of forms, including general- or special-purpose computer systems, either integrated into the manufacturing tool

containing the reaction chamber or separate from the manufacturing tool, such as a laptop or other portable computer system. The control system may be communicatively connected to the power supply 60, or may output current values that are in turn manually inputted to the power supply. Where the control system is connected to the power supply by a network, other computer systems and similar devices may intervene between the control system and the power supply. In many embodiments, the control system contains such components as one or more processors, a primary memory for storing programs and data, a persistent memory for persistently storing programs and data, input/output devices, and a computer-readable medium drive, such as a CD-ROM drive or a DVD drive.

Once the values for the sensitivity table/matrix have been determined, the values may be stored in and used by control system 65 to control one or more of the electrical parameters that power supply 60 uses in connection with each of the individually controllable electrodes 58. Figure 4 is a flow diagram illustrating one manner in which the sensitivity table/matrix may be used to calculate an electrical parameter (*i.e.*, current) for each of the individually controllable electrodes 58 that may be used to meet a process target parameter (*i.e.*, target thickness of the electroplated film).

In the steps shown in Figure 4, the optimizer utilizes two sets of input parameters along with the sensitivity table/matrix to calculate the required electrical parameters. In step 70, the optimizer performs a first plating cycle (a "test run") using a known, predetermined set of electrical parameters. For example, a test run can be performed by subjecting a microelectronic workpiece 25 to an electroplating process in which the current provided to each of the individually controllable electrodes 58 is fixed at a predetermined magnitude for a given period of time.

In step 72, after the test run is complete, the optimizer measures the physical characteristics (*i.e.*, thickness of the electroplated film) of the test workpiece to produce a first set of parameters. For example, in step 72, the test workpiece may be subjected to thickness measurements using a metrology station, producing a set of parameters containing thickness measurements at each of a

number of points on the test workpiece. In step 74, the optimizer compares the physical characteristics of the test workpiece measured in step 72 against a second set of input parameters. In the illustrated embodiment of the method, the second set of input parameters corresponds to the target physical characteristics of the microelectronic workpiece that are to be ultimately achieved by the process (*i.e.*, the thickness of the electroplated film). Notably, the target physical characteristics can either be uniform over the surface of the microelectronic workpiece 25 or vary over the surface. For example, in the illustrated embodiment, the thickness of an electroplated film on the surface of the microelectronic workpiece 25 can be used as the target physical characteristic, and the user may expressly specify the target thicknesses at various radial distances from the center of the workpiece, a grid relative to the workpiece, or other reference systems relative to fiducials on the workpiece.

In step 74, the optimizer uses the first and second set of input parameters to generate a set of process error values. In step 80, the optimizer derives a new electrical parameter set based on calculations including the set of process error values and the values of the sensitivity table/matrix. In step 82, once the new electrical parameter set is derived, the optimizer directs power supply 60 to use the derived electrical parameters in processing the next microelectronic workpiece. Then, in step 404, the optimizer measures physical characteristics of the test workpiece in a manner similar to step 72. In step 406, the optimizer compares the characteristics measured in step 404 with a set of target characteristics to generate a set of process error values. The set of target characteristics may be the same set of target characteristics as used in step 74, or may be a different set of target characteristics. In step 408, if the error values generated in step 406 are within a predetermined range, then the optimizer continues in step 410, else the facility continues in 80. In step 80, the optimizer derives a new electrical parameter set. In step 410, the optimizer uses the newest electrical parameter derived in step 80 in processing subsequent microelectronic workpieces. In some embodiments (not shown), the processed microelectronic workpieces, and/or their measured

characteristics are examined, either manually or automatically, in order to further troubleshoot the process.

With reference again to Figure 3, the first and second set of input parameters may be provided to the control system 65 by a user interface 64 and/or a metrics tool 86. The user interface 64 can include a keyboard, a touch-sensitive screen, a voice recognition system, and/or other input devices. The metrics tool 86 may be an automated tool that is used to measure the physical characteristics of the test workpiece after the test run, such as a metrology station. When both a user interface 64 and a metrics tool 86 are employed, the user interface 64 may be used to input the target physical characteristics that are to be achieved by the process while metrics tool 86 may be used to directly communicate the measured physical characteristics of the test workpiece to the control system 65. In the absence of a metrics tool that can communicate with control system 65, the measured physical characteristics of the test workpiece can be provided to control system 65 through the user interface 64, or by removable data storage media, such as a floppy disk. It will be recognized that the foregoing are only examples of suitable data communications devices and that other data communications devices may be used to provide the first and second set of input parameters to control system 65.

In order to predict change in thickness as a function of change in current, the optimizer generates a Jacobian sensitivity matrix. An example in which the sensitivity matrix generated by the optimizer is based upon a mathematical model of the reaction chamber is discussed below. In additional embodiments, however, the sensitivity matrix used by the optimizer is based upon experimental results produced by operating the actual reaction chamber. The data modeled in the sensitivity matrix includes a baseline film thickness profile and as many perturbation curves as anodes, where each perturbation curve involves adding roughly 0.05 amps to one specific anode. The Jacobian is a matrix of partial derivatives, representing the change in thickness in microns over the change in current in amp minutes. Specifically, the Jacobian is an $m \times n$ matrix where m, the number of rows, is equal to the number of radial location data points in the modeled

data and *n*, the number of columns, is equal to the number of anodes on the reactor. Typically, the value of *m* is relatively large (>100) due to the computational mesh chosen for the model of the chamber. The components of the matrix are calculated by taking the quotient of the difference in thickness due to the perturbed anode and the current change in amp-minutes, which is the product of the current change in amps and the run time in minutes.

As one source of feedback control, the optimizer uses the thickness of the most-recently plated wafer at each of a number of radial positions on the plated wafer. These radial positions may either be selected from the radial positions corresponding to the rows of the matrix, or may be interpolated between the radial positions corresponding to the rows of the matrix. A wide range of numbers of radial positions may be used. As the number of radial positions used increases, the optimizer's results in terms of coating uniformity improves. However, as the number of radial positions used increases, the amount of time required to measure the wafer, to input the measurement results, and/or to operate the optimizer to generate new currents can increase. Accordingly, the smallest number of radial positions that produce acceptable results is typically used. One approach is to use the number of radial test points within a standard metrology contour map (4 for 200mm and 4 or 6 for 300mm) plus one, where the extra point is added to better the 3 sigma uniformity for all the points (*i.e.*, to better the diameter scan).

A specific measurement point map may be designed for the metrology station, which will measure the appropriate points on the wafer corresponding with the radial positions necessary for the optimizer operation.

The optimizer can further be understood with reference to a specific embodiment in which the electrochemical process is electroplating, the thickness of the electroplated film is the target physical parameter, and the current provided to each of the individually controlled electrodes 58 is the electrical parameter that is to be controlled to achieve the target film thickness. In accordance with this specific embodiment, a Jacobian sensitivity matrix is first derived from experimental or numerically simulated data. Figure 5 is a graph of a sample Jacobian sensitivity

matrix for a multiple-electrode reaction chamber. In particular, Figure 5 is a graph of a sample change in electroplated film thickness per change in current-time as a function of radial position on the microelectronic workpiece 25 for each of a number of individually controlled electrodes, such as anodes A1 – A4 shown in Figure 3. A first baseline workpiece is electroplated for a predetermined period of time by delivering a predetermined set of current values to electrodes in the multiple anode reactor. The thickness of the resulting electroplated film is then measured as a function of the radial position on the workpiece. These data points are then used as baseline measurements that are compared to the data acquired as the current to each of the anodes A1 – A4 is perturbated. Line 90 is a plot of the Jacobian terms associated with a perturbation in the current provided by power supply 60 to anode A1 with the current to the remaining anodes A2 – A4 held at their constant predetermined values. Line 92 is a plot of the Jacobian terms associated with a perturbation in the current provided by power supply 60 to anode A2 with the current to the remaining anodes A1 and A3 – A4 held at their constant predetermined values. Line 94 is a plot of the Jacobian terms associated with a perturbation in the current provided by power supply 60 to anode A3 with the current to the remaining anodes A1 – A2 and A4 held at their constant predetermined values. Lastly, line 96 is a plot of the Jacobian terms associated with a perturbation in the current provided by power supply 60 to anode A4 with the current to the remaining anodes A1 - A3 held at their constant predetermined values.

The data for the Jacobian parameters shown in Figure 5 may be computed using the following equations:

$$J_{ij} = \frac{\partial t_i}{\partial AM_j} \cong \frac{t_i(AM + \varepsilon_j) - t_i(AM)}{|\varepsilon_j|} \qquad \text{Equation (A1)}$$

$$t(AM) = [t_1(AM) \quad t_2(AM) \quad \ldots \quad t_m(AM)] \qquad \text{Equation (A2)}$$

$$\boldsymbol{AM} = [AM_1 \quad AM_2 \quad \cdot \quad \cdot \quad AM_n] \qquad \text{Equation (A3)}$$

$$\varepsilon_1 = \begin{bmatrix} \Delta AM_1 \\ 0 \\ \cdot \\ \cdot \\ 0 \end{bmatrix} \quad \varepsilon_2 = \begin{bmatrix} 0 \\ \Delta AM_2 \\ 0 \\ \cdot \\ 0 \end{bmatrix} \quad \ldots \varepsilon_n = \begin{bmatrix} 0 \\ \cdot \\ \cdot \\ 0 \\ \Delta AM_n \end{bmatrix} \qquad \text{Equation (A4)}$$

where:

t represents thickness [microns];

$\boldsymbol{AM}$ represents current [amp-minutes];

ε represents perturbation [amp-minutes];

i is an integer corresponding to a radial position on the workpiece;

j is an integer representing a particular anode;

m is an integer corresponding to the total number of radial positions on the workpiece; and

n is an integer representing the total number of individually-controllable anodes.

The Jacobian sensitivity matrix, set forth below as Equation (A5), is an index of the Jacobian values computed using Equations (A1)-(A4). The Jacobian matrix may be generated either using a simulation of the operation of the deposition chamber based upon a mathematical model of the deposition chamber, or using experimental data derived from the plating of one or more test wafers. Construction of such a mathematical model, as well as its use to simulate operation of the modeled deposition chamber, is discussed in detail in G. Ritter, P. McHugh, G. Wilson and T. Ritzdorf, "Two- and three- dimensional numerical modeling of copper electroplating for advanced ULSI metallization," Solid State Electronics, volume 44, issue 5, pp. 797-807 (May 2000), available from

http://www.elsevier.nl/gej-ng/10/30/25/29/28/27/article.pdf, also available from http://journals.ohiolink.edu/pdflinks/01040215463800982.pdf.

$$J = \begin{vmatrix} 0.192982 & 0.071570 & 0.030913 & 0.017811 \\ 0.148448 & 0.084824 & 0.039650 & 0.022264 \\ 0.066126 & 0.087475 & 0.076612 & 0.047073 \\ 0.037112 & 0.057654 & 0.090725 & 0.092239 \\ 0.029689 & 0.045725 & 0.073924 & 0.138040 \end{vmatrix} \quad \text{Equation (A5)}$$

The values in the Jacobian matrix are also presented as highlighted data points in the graph of Figure 5. These values correspond to the radial positions on the surface of a semiconductor wafer that are typically chosen for measurement. Once the values for the Jacobian sensitivity matrix have been derived, they may be stored in control system 65 for further use.

Table 1 below sets forth exemplary data corresponding to a test run in which a 200mm wafer is plated with copper in a multiple anode system using a nominally 2000 Å thick initial copper seed-layer. Identical currents of 1.12 Amps (for 3 minutes) were provided to all four anodes A1 – A4. The resulting thickness at five radial locations was then measured and is recorded in the second column of Table 1. The 3 sigma uniformity of the wafer is 9.4% using a 49 point contour map. Target thickness were then provided and are set forth in column 3 of Table 1. In this example, because a flat coating is desired, the target thickness is the same at each radial position. The thickness errors (processed errors) between the plated film and the target thickness were then calculated and are provided in the last column of Table 1. These calculated thickness errors are used by the optimizer as a source of feedback control.

TABLE 1. DATA FROM WAFER PLATED WITH 1.12 AMPS TO EACH ANODE.

Radial Location (m)	Measured Thickness (microns)	Target Thickness (microns)	Error (microns)
0	1.1081	1.0291	-0.0790
0.032	1.0778	1.0291	-0.0487
0.063	1.0226	1.0291	0.0065
0.081	1.0169	1.0291	0.0122
0.098	0.09987	1.0291	0.0304

The Jacobian sensitivity matrix may then be used along with the thickness error values to provide a revised set of anode current values that should yield better film uniformity. The equations summarizing this approach are set forth below:

$$\Delta AM = J^{-1}\Delta t$$ (for a square system in which the number of measured radial positions corresponds to the number of individually controlled anodes in the system); and Equation (B1)

$$\Delta AM = \left(J^T J\right)^{-1} J^T \Delta t$$ (for a non-square system in which the number of measured radial positions is different than the number of individually controlled anodes in the system). Equation (B2)

$$\Delta t_i = t_i^{target} - t_i^{old} - (t_i^{newseed} - t_i^{old\,seed}) + t_i^{specified}$$ Equation (B3)

In Equation (B3), t_i^{target} is the target thickness required to obtain a wafer of desired profile while considering the total current adjustment, t_i^{old} is the old overall thickness, $t_i^{newseed}$ is the thickness of the new seed layer, $t_i^{oldseed}$ is the thickness of the old seed layer, and $t_i^{specified}$ is the thickness specification relative to the center of the wafer, that is, the thickness specified by the target plating profile. In particular, the term $t_i^{specified}$ represents the target thickness, while the quantity $t_i^{target} - t_i^{old}$ represents feedback from the previous wafer, and the quantity $t_i^{newseed} - t_i^{oldseed}$ represents feedforward from the thickness of the seed layer of the incoming wafer -- to disable feedback control, the first quantity is omitted from equation (B3); to disable feedforward control, the second quantity is omitted from equation (B3).

Table 2 shows the foregoing equations as applied to the given data set and the corresponding current changes that have been derived from the equations to meet the target thickness at each radial location (best least square fit). Such application of the equations, and construction of the Jacobian matrix is in some embodiments performed using a spreadsheet application program, such as Microsoft Excel®, in connection with specialized macro programs. In other embodiments, different approaches are used in constructing the Jacobian matrix and applying the above equations.

The wafer uniformity obtained with the currents in the last column of Table 2 was 1.7% (compared to 9.4% for the test run wafer). This procedure can be repeated again to try to further improve the uniformity. In this example, the differences between the seed layers were ignored since the seed layers are substantially the same.

TABLE 2. CURRENT ADJUSTMENT

Anode #	Anode Currents for Run #1 (Amps)	Change to Anode Currents (Amps)	Anode Currents for Run #2 (Amps)
1	1.12	-0.21	0.91
2	1.12	0.20	1.32
3	1.12	-0.09	1.03
4	1.12	0.10	1.22

Once the corrected values for the anode currents have been calculated, control system 65 of Figure 3 directs power supply 60 to provide the corrected current to the respective anode A1 – A4 during subsequent processes to meet the target film thickness and uniformity.

In some instances, it may be desirable to iteratively apply the foregoing equations to arrive at a set of current change values (the values shown in column 3 of Table 2) that add up to zero. For example, doing so enables the total plating charge—and therefore the total mass of plated material—to be held constant without having to vary the recipe time.

The Jacobian sensitivity matrix in the foregoing example quantifies the system response to anode current changes about a baseline condition. Ideally, a different matrix may be employed if the processing conditions vary significantly from the baseline. The number of system parameters that may influence the sensitivity values of the sensitivity matrix is quite large. Such system parameters include the seed layer thickness, the electrolyte conductivity, the metal being plated, the film thickness, the plating rate, the contact ring geometry, the wafer position relative to the chamber, and the anode shape/current distribution. Anode shape/current distribution is included to accommodate chamber designs where changes in the shape of consumable anodes over time affect plating characteristics of the chamber. Changes to all of these items can change the current density across

the wafer for a given set of anode currents and, as a result, can change the response of the system to changes in the anode currents. It is expected, however, that small changes to many of these parameters will not require the calculation of a new sensitivity matrix. Nevertheless, a plurality of sensitivity tables/matrices may be derived for different processing conditions and stored in control system 65. Which of the sensitivity tables/matrices is to be used by the control system 65 can be entered manually by a user, or can be set automatically depending on measurements taken by certain sensors or the like (*i.e.*, temperature sensors, chemical analysis units, etc.) that indicate the existence of one or more particular processing conditions.

The optimizer may also be used to compensate for differences and non-uniformities of the initial seed layer of the microelectronic workpiece. Generally stated, a blanket seed layer can affect the uniformity of a plated film in two ways:

1. If the seed layer non-uniformity changes, this non-uniformity is added to the final film. For example, if the seed layer is 100 Å thinner at the outer edge than expected, the final film thickness may also be 100 Å thinner at the outer edge.

2. If the average seed-layer thickness changes significantly, the resistance of the seed-layer will change resulting in a modified current density distribution across the wafer and altered film uniformity. For example, if the seed layer decreases from 2000 Å to 1000 Å, the final film will not only be thinner (because the initial film is thinner) but it will also be relatively thicker at the outer edge due to the higher resistivity of the 1000 Å seed-layer compared to the 2000 Å seed-layer (assuming an edge contact).

The optimizer can be used to compensate for such seed-layer deviations, thereby utilizing seed-layer thicknesses as a source of feed-forward control. In the first case above, the changes in seed-layer uniformity may be handled in the same manner that errors between target thickness and measured thickness are handled. A pre-measurement of the wafer quantifies changes in the

seed-layer thickness at the various radial measurement locations and these changes (errors) are figured into the current adjustment calculations. Using this approach, excellent uniformity results can be obtained on the new seed layer, even on the first attempt at electroplating.

In the second case noted above, an update of or selection of another stored sensitivity/Jacobian matrix can be used to account for a significantly different resistance of the seed-layer. A simple method to adjust for the new seed layer thickness is to plate a film onto the new seed layer using the same currents used in plating a film on the previous seed layer. The thickness errors measured from this wafer can be used with a sensitivity matrix appropriate for the new seed-layer to adjust the currents.

To further illuminate the operation of the optimizer, a second test run is described. In the second test run, the optimization process begins with a baseline current set or standard recipe currents. A wafer must be pre-read for seed layer thickness data, and then plated using the indicated currents. After plating, the wafer is re-measured for the final thickness values. The following wafer must also be pre-read for seed layer thickness data. Sixty-seven points at the standard five radial positions (0mm, 31.83mm, 63.67mm, 80mm, 95.5mm) are typically measured and averaged for each wafer reading.

The thickness data from the previous wafer, and the new wafer seed layer, in addition to the anode currents, are entered into the input page of the optimizer. The user may also elect to input a thickness specification, or chose to modify the plating thickness by adjusting the total current in amp-minutes. After all the data is correctly inputted, the user activates the optimizer. In response, the optimizer predicts thickness changes and calculates new currents.

The new wafer is then plated with the adjusted anode currents and then measured. A second modification may be required if the thickness profile is not satisfactory.

When a further iteration is required, the optimization is continued. As before, the post- plated wafer is measured for thickness values, and another wafer is

pre-read for a new seed set of seed layer thickness values. Then, the following quantities are entered on the input page:

1. plated wafer thickness,
2. anode currents,
3. plated wafer seed layer thickness, and
4. new wafer seed layer thickness

The recipe time and thickness profile specification should be consistent with the previous iteration. The program is now ready to be run again to provide a new set of anode currents for the next plating attempt.

After plating with the new currents, the processed wafer is measured and if the uniformity is still not acceptable, the procedure may be continued with another iteration. The standard value determining the uniformity of a wafer is the 3-σ, which is the standard deviation of the measured points relative to the mean and multiplied by three. Usually a forty-nine point map is used with measurements at the radial positions of approximately 0mm, 32mm, 64mm, and 95mm to test for uniformity.

The above procedure will be demonstrated using a multi-iteration example. Wafer #3934 is the first plated wafer using a set of standard anode currents: 0.557/ 0.818/ 1.039/ 0.786 (anode1/ anode2/ anode3/ anode4 in amps) with a recipe time of 2.33 minutes (140 seconds). Before plating, the wafer is pre-read for seed layer data. These thickness values, in microns, from the center to the outer edge, are shown in Table 3:

TABLE 3. SEED LAYER THICKNESS VALUES FOR WAFER #3934

Radius (mm)	Thickness (μm)
0.00	0.130207
31.83	0.13108
63.67	0.131882
80.00	0.129958
95.50	0.127886

The wafer is then sent to the plating chamber, and then re-measured after being processed. The resulting thickness values (in microns) for the post-plated wafer #3934 are shown in Table 4:

TABLE 4. THICKNESS VALUES FOR POST-PLATED WAFER #3934

Radius (mm)	Thickness (μm)
0.00	0.615938
31.83	0.617442
63.67	0.626134
80.00	0.626202
95.50	0.628257

The 3-σ for the plated wafer is calculated to be 2.67% over a range of 230.4 Angstroms. Since the currents are already producing a wafer below 3%, any adjustments are going to be minor. The subsequent wafer has to be pre-read for

seed layer values in order to compensate for any seed layer differences. Wafer #4004 is measured and the thickness values in microns are shown in Table 5:

TABLE 5. SEED LAYER THICKNESS VALUES FOR WAFER #4004

Radius (mm)	Thickness (μm)
0.00	0.130308
31.83	0.131178
63.67	0.132068
80.00	0.13079
95.50	0.130314

For this optimization run, there is no thickness profile specification, or overall thickness adjustment. All of the preceding data is inputted into the optimizer, and the optimizer is activated to generate a new set of currents. These currents will be used to plate the next wafer. Figure 6 is a spreadsheet diagram showing the new current outputs calculated from the inputs for the first optimization run. It can be seen that the input values 601 have generated output 602, including a new current set. The optimizer has also predicted the absolute end changed thicknesses 603 that this new current set will produce.

The new anode currents are sent to the process recipe and run in the plating chamber. The run time and total currents (amp-minutes) remain constant, and the current density on the wafer is unchanged. The new seed layer data from this run for wafer #4004 will become the old seed layer data for the next iteration.

The thickness (microns) resulting from the adjusted currents plated on wafer #4004 are shown in Table 6:

TABLE 6. THICKNESS VALUES FOR POST-PLATED WAFER #4004

Radius (mm)	Thickness (μm)
0.00	0.624351
31.83	0.621553
63.67	0.622704
80.00	0.62076
95.50	0.618746

The post-plated wafer has a 3-σ of 2.117% over a range of 248.6 Angstroms. To do another iteration, a new seed layer measurement is required, unless notified that the batch of wafers has equivalent seed layers. Wafer # 4220 is pre-measured and the thickness values in microns are shown in Table 7:

TABLE 7. SEED LAYER THICKNESS VALUES FOR WAFER #4220

Radius (mm)	Thickness (μm)
0.00	0.127869
31.83	0.129744
63.67	0.133403
80.00	0.134055
95.50	0.1335560

Again, all of the new data is inputted into the optimizer, along with the currents used to plate the new wafer and the thickness of the plated wafer's seed. The optimizer automatically transfers the new currents into the old currents among the inputs. The optimizer is then activated to generate a new set of currents. Figure 7 is a spreadsheet diagram showing the new current outputs calculated from the inputs for the second optimization run. It can be seen that, from input value 701, the optimizer has produced output 702 including a new current set. It can further be seen that that the facility has predicted absolute and changed thicknesses 703 that will be produced using the new currents.

The corrected anode currents are again sent to the recipe and applied to the plating process. The 2nd adjustments on the anode currents produce the thickness values in microns shown in Table 8:

TABLE 8. THICKNESS VALUES FOR POST-PLATED WAFER #4220

Radius (mm)	Thickness (μm)
0.00	0.624165
31.83	0.622783
63.67	0.626911
80.00	0.627005
95.50	0.623823

The 3-σ for wafer #4220 is 1.97% over a range of 213.6 Angstroms. The procedure may continue to better the uniformity, but the for the purpose of this explanation, a 3-σ below 2% is acceptable.

The optimizer may also be used to compensate for reactor-to-reactor variations in a multiple reactor system, such as the LT-210C™ available from Semitool, Inc., of Kalispell, Montana. In such a system, there is a possibility that the anode currents required to plate a specified film might be different on one reactor when compared to another. Some possible sources for such differences include variations in the wafer position due to tolerances in the lift-rotate mechanism, variations in the current provided to each anode due to power supply manufacturing tolerances, variations in the chamber geometry due to manufacturing tolerances, variations in the plating solution, etc.

In a single anode system, the reactor-to-reactor variation is typically reduced either by reducing hardware manufacturing tolerances or by making slight hardware modifications to each reactor to compensate for reactor variations. In a multiple anode reactor constructed in accordance with the teachings of the present invention, reactor-to-reactor variations can be reduced/eliminated by running slightly different current sets in each reactor. As long as the reactor variations do not fundamentally change the system response (*i.e.*, the sensitivity matrix), the self-tuning scheme disclosed herein is expected to find anode currents that meet film thickness targets. Reactor-to-reactor variations can be quantified by comparing differences in the final anode currents for each chamber. These differences can be saved in one or more offset tables in the control system 65 so that the same recipe may be utilized in each reactor. In addition, these offset tables may be used to increase the efficiency of entering new processing recipes into the control system 65. Furthermore, these findings can be used to trouble-shoot reactor set up. For example, if the values in the offset table are over a particular threshold, the deviation may indicate a hardware deficiency that needs to be corrected.

As mentioned above, embodiments of the optimizer may be used to set currents and other parameters for complex deposition recipes that specify changes in current during the deposition cycle. As an example, embodiments of the optimizer may be used to determine anode currents in accordance with recipe having two different steps. Step 1 of the recipe lasts for .5 minutes, during which a

total of +1 amp of current is delivered through four electrodes. Step 2 of the recipe, which immediately follows step 1, is 1.25 minutes long. During step 2, a total current of +9 amps is delivered for 95 milliseconds. Immediately afterwards, a total current of -4.3 amps is delivered for 25 milliseconds. Ten milliseconds after delivery of the -4.3 amp current is concluded, the cycle repeats, delivering +9 amps for another 95 milliseconds. The period during which a positive current is being delivered is known as the "forward phase" of the step, while the time during which a negative current is being delivered is known as the "backward phase" of the step. Backward phases may be used, for example, to reduce irregularities formed in the plated surface as the result of organic substances within the plating solution.

In order to apply the optimizer to optimize currents for this recipe, initial currents are chosen in accordance with the recipe. These are shown below in Table 9.

Table 9: Initial Multi-step Recipe

		Step 1	Step 2
1.	time	0.5	1.25
2.	forward fraction	1	0.730769
3.	anode 1 current	0.2	1.8
4.	anode 2 current	0.24	2.16
5.	anode 3 current	0.34	3.06
6.	anode 4 current	0.22	1.98
7.	backward fraction		0.192307
8.	anode 1 current		-0.86
9.	anode 2 current		-1.03
10.	anode 3 current		-1.46
11.	anode 4 current		-0.95
12.	forward amp-min	0.5	8.221153
13.	backward amp-min	0	-1.033653
14.	Total Amp-min	7.6875	

The left-hand column of Table 9 shows currents and other information for the first step of the recipe, while the right-hand column shows currents and other information for the second step of the recipe. In line 1, it can be seen that step 1 has a duration of .5 minutes, while step 2 has a duration of 1.25 minutes. In line 2, it

can be seen that, in step 1, forward plating is performed for 100% of the duration of the step, while in step 2, forward plating is performed for about 73% of the duration of the step (95 milliseconds out of the 130 millisecond period of the step). Lines 3-6 show the currents delivered through each of the anodes during the forward phase of each of the two steps. For example, it can be seen that .24 amps are delivered through anode 2 for the duration of step 1. In line 7, it can be seen that a negative current is delivered for about 19% of the duration of step 2 (25 milliseconds out of the total period of 130 milliseconds). Lines 8-11 show the negative currents delivered during the backward phase of step 2. Line 12 shows the charge, in amp-minutes, delivered in the forward phase of each step. For step 1, this is .5 amp-minutes, computed by multiplying the step 1 duration of .5 minutes by the forward fraction of 1, and by the sum of step 1 forward currents, 1 amp. The forward plating charge for step 2 is about 8.22 amp-minutes, computed by multiplying the duration of step 2, 1.25 minutes, by the forward fraction of about 73%, and by the sum of the forward currents in step 2, 9 amps. Line 13 shows the results of a similar calculation for the backward phase of step 2. Line 14 shows the net plating charge, 7.6875 amp-minutes obtained by summing the signed charge values on lines 12 and 13.

The deposition chamber is used to deposit a wafer in accordance with these initial currents. That is, during the first half-minute of deposition (step 1), +.2 amps are delivered through anode 1. During the next 1.25 minutes of the process (step 2), +1.8 amps are delivered through anode 1 for 95 milliseconds, then -0.86 amps are delivered through anode 1 for 25 milliseconds, then no current flows through 1 for 10 milliseconds, and then the cycle is repeated until the end of the 1.25 minute duration of step 2. Overall, the charge of 1.537 amp-minutes is delivered through anode 1. This value is determined by multiplying duration, forward fraction, and anode 1 current from step 1, then adding the product of the duration of step 2, the forward fraction of step 2, and the forward anode 1 current of step 2, then adding the product of the duration of step 2, the backward fraction of

step 2, and the backward anode 1 current of step 2. Such net plating charges may be calculated for each of the anodes, as shown below in Table 10.

Table 10: Net Plating Charges in Initial Multi-step Recipe

Anode1	1.537 Amp-min
Anode2	1.845 Amp-min
Anode3	2.614 Amp-min
Anode4	1.690 Amp-min

These plating charge values are submitted to the optimizer together with thicknesses measured from the wafer plated using the initial current. In response, the optimizer generates a set of new net plating charges for each electrode. These new net plating charges are shown below in Table 11.

Table 11: New Net Plating Charges for Revised Recipe

Anode1	1.537 Amp-min + 0.171286 Amp-min = 1.709 Amp-min
Anode2	1.845 Amp-min - 0.46657 Amp-min = 1.379 Amp-min
Anode3	2.614 Amp-min + 0.106337 Amp-min = 1.271 Amp-min
Anode4	1.690 Amp-min + 0.188942 Amp-min = 1.879 Amp-min

The optimizer then computes for each anode a share of the current to be delivered through the anode by dividing the new net plating charge determined for the anode by the sum of the net plating charges determined for all of the anodes. These current shares are shown below in Table 12.

Table 12: Current Shares for Revised Recipe

Anode1	1.709/7.6875 = 22.2%
Anode2	1.379/7.6875 = 17.9%
Anode3	1.271/7.6875 = 35.5%
Anode4	1.879/7.6875 =24.4%

The optimizer then determines a new current for each anode in each step and phase of the recipe by multiplying the total current for the step and phase by the current share computed for each anode. These are shown in Table 13 below.

Table 13: Revised Multi-Step Recipe

		Step 1	Step 2
1.	time	0.5	1.25
2.	forward fraction	1	0.730769
3.	anode 1 current	0.222281	2.000530
4.	anode 2 current	0.179371	1.614339
5.	anode 3 current	0.353895	3.185055
6.	anode 4 current	0.244452	2.200075
7.	backward fraction		0.192307
8.	anode 1 current	0	-0.955808
9.	anode 2 current	0	-0.771295
10.	anode 3 current	0	-1.521748
11.	anode 4 current	0	-1.051147
12.	forward amp-min	0.5	8.221153
13.	backward amp-min	0	-1.033653
14.	Total Amp-min	7.6875	

For example, it can be seen in line 4 of Table 13 that the forward anode 2 current for step 2 is about 1.61 amps, computed by multiplying the +9 amps total current for the forward phase of step 2 by the current share of 17.9% computed for anode 2 shown in Table 12.

By comparing Table 13 to Table 9, it can be seen that the net plating charge changes specified by the optimizer for the revised recipe are distributed evenly across the steps and phases of this recipe. It can also be seen that the total plating charge for each step and phase of the revised recipe, as well as the total plating charge, is unchanged from the initial multistep recipe. The optimizer may utilize various other schemes for distributing plating charge changes within the recipe. For example, it may alternatively distribute all the changes to step 2 of the recipe, leaving step 1 of the recipe unchanged from the initial multi-step recipe. In some embodiments, the optimizer maintains and applies a different sensitivity matrix for each step in a multi-step recipe.

In some embodiments, the facility utilizes a form of predictive control feedback. In these embodiments, the optimizer generates, for each set of revised currents, a set of predicted plating thicknesses. The optimizer determines the difference between these predicted thicknesses and the actual plated thicknesses of

the corresponding workpiece. For each workpiece, this set of differences represents the level of error produced by the optimizer in setting currents for the workpiece. The optimizer uses the set of differences for the previous workpiece to improve performance on the incoming workpiece by subtracting these differences from the target thickness changes to be effected by current changes for the incoming workpiece. In this way, the optimizer is able to more quickly achieve the target plating profile.

Further sample wafer processing processes employing the optimizer are discussed below. It should be noted that no attempt is made to exhaustively list such processes, and that those included are merely exemplary.

Table 13 below shows a sample wafer processing process employing the optimizer, from which a subset of the steps may be selected and/or modified to define additional such processes.

Table 13: Sample Wafer Processing Process Employing Optimizer

Step	Tool/Process
1.	Deposit metal seed layer using one or more physical vapor deposition ("PVD") tools, different chambers on the same PVD tool, or CVD chambers or electroless deposition chambers.
2.	Measure seed layer film thickness using metrology station, either on the tool or an independent station – metrology stations can infer film thickness from sheet resistance measurements or from optical measurements of the film
3.	Apply optimizer -- residing on tool or off tool on a personal computer -- in a seed layer enhancement ("SLE") chamber using measurements from step 2 (feedforward) and measurement results from previous SLE wafer on step 6 or 8 (feedback)
4.	Deposit metal layer in SLE chamber
5.	Rinse wafer in SRD/Capsule chamber
6.	Measure wafer thickness using Metrology Station
7.	Anneal wafer in annealing chamber on the tool or in independent stations
8.	Measure wafer thickness using Metrology Station
9.	Apply optimizer in ECD chamber using measurements from step 7 (feedforward) and measurement results from previous ECD wafer on step 12 or 14 (feedback)
10.	Deposit final metal layer in ECD chamber
11.	Clean and bevel etch wafer in Capsule chamber
12.	Measure wafer thickness using Metrology Station
13.	Anneal wafer in anneal chamber
14.	Measure wafer thickness using Metrology Station

These steps may be qualified in a variety of ways including: the measurement/optimizer sequence steps can be performed during tool qualification or "dial-in"; the measurement/optimizer sequence steps sequence can be performed periodically to monitor performance; the measurement/optimizer sequence steps sequence can be performed on each wafer; SLE process may be optional depending upon the measurement results in step 2 (*i.e.*, this wafer may routed around this and associated process steps); wafer sequence may be terminated, rerouted, or restarted based upon the measurement results of step 2, 6, 8, 12, and 14; measurement/optimizer steps may be performed only after process/hardware changes; measurements before and after annealing (*e.g.*, sheet resistance) may be used to determine effectiveness of annealing process; metal deposition steps 4 and 10 may be deposition of same metals or different metals -- they could deposit the same metal using different baths; one or more metal deposition steps could be used, which deposit one or more different metals; the optimization steps may adjust currents to generate a flat thickness profile or one with a specified shape; the optimization steps may adjust current to generate a desired current density profile for future filling; the wafer may be returned to a deposition chamber for additional metal deposition if the film thickness is insufficient, based upon metrology results.

Table 14 below shows an additional sample process:

Table 14: Sample Wafer Processing Process Employing Optimizer

Step	Tool/Process
1.	Deposit metal seed layer using PVD tool
2.	Measure seed layer film thickness using metrology station
3.	Apply optimizer in ECD chamber using measurements from step 2 (feedforward) and measurement results from previous ECD wafer on step 7 (feedback)
4.	Deposit final metal layer in ECD chamber
5.	Anneal wafer in anneal chamber
6.	Clean and bevel etch wafer in Capsule chamber
7.	Measure wafer thickness using Metrology Station

Table 15 below shows an additional sample process:

Table 15: Sample Wafer Processing Process Employing Optimizer

Step	Tool/Process
1.	Deposit metal seed layer using PVD tool
2.	Measure seed layer film thickness using metrology station
3.	Apply optimizer in ECD chamber using measurements from step 2 (feedforward) and measurement results from previous ECD wafer on step 6 (feedback)
4.	Deposit final metal layer in ECD chamber
6.	Clean and bevel etch wafer in Capsule chamber
7.	Measure wafer thickness using Metrology Station

Table 16 below shows an additional sample process:

Table 16: Sample Wafer Processing Process Employing Optimizer

Step	Tool/Process
1.	Deposit metal seed layer using PVD tool
2.	Measure seed layer film thickness using metrology station
3.	Apply optimizer in ECD chamber using measurements from step 2 (feedforward) and measurement results from previous SLE wafer on step 6 (feedback)
4.	Deposit metal layer in SLE chamber
6.	Clean and bevel etch wafer in Capsule chamber
7.	Measure wafer thickness using Metrology Station

As an additional sample process, the thickness uniformity of a wafer with a PVD-deposited seed layer is measured on a dedicated metrology tool, after which the wafer is brought to the plating tool and placed in an SLE process chamber. Using the measurements from the dedicated metrology tool, the optimizer is used to select an SLE recipe that will augment the PVD-deposited seed layer to yield a seed layer with improved thickness uniformity, and the SLE process is performed on the wafer. After the wafer has been cleaned and dried in one of the plating tool capsule chambers, the wafer is transferred to a plating chamber where the optimizer is then used to select a plating recipe that will yield a uniform bulk film, at the desired thickness, based on the nominal seed layer thickness. After the bulk film plating process has completed, the wafer is transferred to a capsule cleaning chamber, whereupon it is removed from the tool.

As an additional sample process, a wafer is brought to the plating tool and placed in the on-board metrology station to determine the thickness profile of the CVD-deposited seed layer. The wafer is then transferred to a plating chamber. Using the seed layer measurements from the on-board metrology station, the optimizer is used to select a plating recipe that will yield a convex (center-thick) bulk film, at the desired nominal thickness. After the plating process has completed, the wafer is transferred to a capsule cleaning chamber, whereupon it is removed from the tool.

As an additional sample process, a wafer comes to an electroplating tool with a seed layer, applied using physical vapor deposition, that is non-uniform. A metrology station is used to measure the non-uniformity, and the optimizer operates the multiple-electrode reactor to correct the measured non-uniformity. Seed layer repair is then performed using an electroless ion plating process to produce a final, more uniform, seed layer. The optimizer then operates to deposit bulk metal onto the repaired seed layer.

As an additional sample process, a semiconductor fabricator has two physical vapor deposition tools ("PVD tools"), each of which has its own particular characteristics. A wafer processed by the first PVD tool and having a seed layer non-uniformity is directed to a first multiple-electrode reactor for seed layer repair. A wafer from the second PVD tool that has a different seed layer non-uniformity is directed to a second multiple-electrode reactor for seed layer repair. Bulk metal is then deposited onto the repaired seed layers of the two wafers in a third CFD reactor under the control of the optimizer.

Additional applications of the optimizer include:

Single plating example: The production environment can involve many recipes on a tool because each wafer may require multiple processing steps. For example, there may be 5-7 metal interconnect layers and each of the layers have different process parameters. Furthermore, a tool may be processing several different products. The advantage having a multiple anode reactor on the tool (like

the CFD reactor) is that unique anode currents and optimal performance may be specified for all the different recipes on all the different chambers on the tool.

A basic application of the optimizer is to aid in the initial dial-in process for all of the recipes that are going to be run on a tool in production. In this mode, recipes will be written and tested experimentally prior to production, using the optimizer as an aid to obtained uniformity specifications. In this picture of workpiece production, the optimizer is used during the set-up phase only, saving the process engineer much time in setting up the tool and each of the recipes. If seed-layers coming into the tool are identical and stable, the above picture is sufficient.

If the seed-layers are not consistent, then off-tool metrology or integrated metrology can be used to monitor the changes in the seed-layers and the optimizer can be used to modify the anode currents in the recipe to compensate for these variations.

ECD seed followed by bulk ECD: In the case of sequential plating steps, metrology before and after each plating step allows for recipe current adjustments with the optimizer to each process. In the case of ECD seed, the initial PVD or CVD layer of metal can be measured and adjusted for using the feed-forward feature of the optimizer. Note: In this process the resistance of the barrier layer under the seed layer can also have a large influence on the plating uniformity, if the resistance of this layer can be measured, then the optimizer can be used to compensate for this effect (it may take more than one iteration of the optimizer).

Dial-In Uniform Current Density Recipes: Using the optimizer and metrology the optimizer can be used to help dial in recipes that insure uniform current density during the feature filling step.

Table Look-Up: The optimal currents to plate uniformly on different thickness seed-layers (assuming the seed layers are substantially uniform) can be determined in advance, using the optimizer to find these currents. Then the currents can be pulled from a table, when the resistivity of the seed layer is measured. This may be quite useful for platen plating (solder) where the seed layer resistance is constant for the whole plating run.

It is envisioned that the optimizer may be used in one or more stages of widely-varying processes for processing semiconductor workpieces. It is further envisioned that the optimizer may operate completely separately from the processing tools performing such processes, with only some mechanism for the optimizer to pass control parameters to such processing tools. Indeed, the optimizer and processing tools may be operated under the control and/or ownership of different parties, and/or in different physical locations.

Numerous modifications may be made to the described optimizer without departing from the basic teachings thereof. For example, although the present invention is described in the context of electrochemical processing of the microelectronic workpiece, the teachings herein can also be extended to other types of microelectronic workpiece processing, including various kinds of material deposition processes. For example, the optimizer may be used to control electrophoretic deposition of material, such as positive or negative electrophoretic photoresists or electrophoretic paints; chemical or physical vapor deposition; etc. In effect, the teachings herein can be extended to other microelectronic workpiece processing systems that have individually controlled processing elements that are responsive to control parameters and that have interdependent effects on a physical characteristic of the microelectronic workpiece that is processed using the elements. Such systems may employ sensitivity tables or matrices as set forth herein and use them in calculations with one or more input parameters sets to arrive at control parameter values that accurately result in the targeted physical characteristic of the microelectronic workpiece. Although the present invention has been described in substantial detail with reference to one or more specific embodiments, those of skill in the art will recognize that changes may be made thereto without departing from the scope and spirit of the invention as set forth herein.

CLAIMS

We claim:

1. A method in a computing system for controlling an electroplating process in which a sequence of workpieces are electroplated with a material each in an electroplating cycle, such controlling including designating, for each electroplated workpiece, currents supplied to each of a plurality of electroplating anodes, comprising:

constructing a Jacobian sensitivity matrix characterizing the effects on plated material thickness at each of a plurality of workpiece positions of varying the currents supplied each of the plurality of anodes;

receiving a specification of target plating material thickness at each of the plurality of workpiece positions;

applying the Jacobian sensitivity matrix to make a first determination of how a baseline set of anode currents should be varied to produce the specified target plating material thicknesses rather than baseline plating material thicknesses indicated to result from the baseline set of anode currents;

generating an indication to conduct a first electroplating cycle with respect to a first workpiece using a designated set of anode currents produced by varying the baseline set of anode currents in accordance with the first determination;

receiving measured plating material thicknesses thickness at each of the plurality of workpiece positions of the first workpiece;

applying the Jacobian sensitivity matrix to make a second determination of how the set of anode currents designated for the first electroplating cycle should be varied to produce the specified target plating material thicknesses rather than measured plating material thicknesses of the first workpiece; and

generating an indication to conduct a second electroplating cycle with respect to a second workpiece using a designated set of anode currents produced by

varying the set of anode currents designated for the first electroplating cycle in accordance with the second determination.

2. The method of claim 1, further comprising:

receiving measured plating material thicknesses at each of the plurality of workpiece positions from the second electroplating cycle;

determining that the measured plating material thicknesses from the second electroplating cycle are within a specified tolerance of the specified target plating material thicknesses; and

in response to the determination, generating one or more indications to conduct a plurality of further electroplating cycles using the set of anode currents designated for the second electroplating cycle.

3. The method of claim 1, further comprising:

receiving measured plating material thicknesses at each of the plurality of workpiece positions from the second electroplating cycle;

applying the Jacobian sensitivity matrix to make a third determination of how the set of anode currents designated for the second electroplating cycle should be varied to produce the specified target plating material thicknesses rather than measured plating material thicknesses of the second workpiece; and

generating an indication to conduct a third electroplating cycle using a designated set of anode currents produced by varying the set of anode currents designated for the second electroplating cycle in accordance with the second determination.

4. The method of claim 1, further comprising:

before the first electroplating cycle, receiving measured seed layer thicknesses of the first workpiece at each of the plurality of workpiece positions; and

before the second electroplating cycle, receiving measured seed layer thicknesses of the second workpiece at each of the plurality of workpiece positions,

and wherein the second determination made by applying the Jacobian sensitivity matrix is a determination of how the set of anode currents designated for the first electroplating cycle should be varied to produce the specified target plating material thicknesses rather than measured plating material thicknesses of the first workpiece in light of the differences between the measured seed layer thicknesses of the first and second workpieces.

5. The method of claim 1 wherein the Jacobian sensitivity matrix is generated from a mathematical model of the electroplating process.

6. The method of claim 1 wherein the Jacobian sensitivity matrix is generated from data obtained by operating the electroplating process.

7. The method of claim 1 wherein the baseline plating material thicknesses are generated from data obtained by simulating operation of the electroplating process using a mathematical model of the electroplating process, the simulation using the baseline anode currents.

8. The method of claim 1 wherein the baseline plating material thicknesses are generated from data obtained by operating the electroplating process with the baseline anode currents.

9. A method in a computing system for providing closed-loop control of a process for applying a coating material to a series of workpieces to produce a coating layer of the coating material, comprising:

(a) receiving a coating profile specifying one or more attributes of the coating layer to be produced on the workpieces;

(b) designating a first set of coating parameters for use in coating a first workpiece;

(c) identifying a first set of discrepancies between attributes of the coating layer produced on the first workpiece using the first set of coating parameters and the attributes specified by the coating profile;

(d) determining a first set of modifications to the first set of coating parameters expected to reduce the identified first set of discrepancies;

(e) modifying the first set of coating parameters in accordance with the determined first set of modifications to produce a second set of coating parameters;

(f) designating the second set of coating parameters for use in coating a second workpiece; and

(g) repeating (c) – (f) for subsequent workpieces in the series until the identified set of discrepancies falls within a selected tolerance.

10. The method of claim 9, further comprising, after (g), designating the most recently-produced set of coating parameters for use in coating subsequent workpieces.

11. The method of claim 9 wherein each workpiece is a silicon wafer.

12. The method of claim 9 wherein the coating material is a conductor.

13. The method of claim 9 wherein the coating material is copper.

14. The method of claim 9 wherein the process is performed in an electrolysis chamber having a plurality of anodes, and wherein at least a portion of

the coating parameters are currents to transmit through identified anodes among the plurality of anodes.

15. The method of claim 9 wherein at least a portion of the attributes of the coating layer to be produced on the workpieces specified by the coating profile are target thicknesses of the coating layer in selected regions on the workpiece.

16. The method of claim 15 wherein the discrepancies identified in (c) correspond to differences between thicknesses measured in the selected regions on the coated workpiece and the target thicknesses specified by the coating profile for the selected regions on the workpiece.

17. The method of claim 15, further comprising:

generating a set of predicted coating thicknesses in the selected regions on the first workpiece based upon the first set of coating parameters;

receiving an indication of thicknesses measured in the selected regions on the coated first workpiece;

computing a difference between the predicted coating thicknesses and the indicated measured thicknesses; and

subtracting the computed difference from the determined first set of modifications before using the first set of modifications to modify the first set of coating parameters.

18. The method of claim 15 wherein each of the workpieces bears a seed layer,

the method further comprising:

for each the first and second workpieces, receiving an indication of seed layer thicknesses measured in the selected regions on the workpiece before the workpiece is coated; and

before designating the second set of coating parameters for use in coating a second workpiece, further adjusting the second set of coating parameters in to adjust for differences between the measured thicknesses of the first and second workpieces.

19. The method of claim 9 wherein the coating process is electrolytic deposition.

20. The method of claim 9 wherein the coating process is electrophoretic deposition.

21. The method of claim 9 wherein the coating process is chemical vapor deposition.

22. The method of claim 9 wherein the coating process is physical vapor deposition.

23. The method of claim 9 wherein the coating process is electron beam atomization.

24. The method of claim 9 wherein (d) utilizes a sensitivity matrix mapping changes in attributes to changes in coating parameters expected to produce those attribute changes.

25. A computer-readable medium whose contents cause a computing system to provide closed-loop control of a process for applying a coating material to a series of workpieces to produce a coating layer of the coating material by:

(a) receiving a coating profile specifying one or more attributes of the coating layer to be produced on the workpieces;

(b) designating a first set of coating parameters for use in coating a first workpiece;

(c) identifying a first set of discrepancies between attributes of the coating layer produced on the first workpiece using the first set of coating parameters and the attributes specified by the coating profile;

(d) determining a first set of modifications to the first set of coating parameters expected to reduce the identified first set of discrepancies;

(e) modifying the first set of coating parameters in accordance with the determined first set of modifications to produce a second set of coating parameters; and

(f) designating the second set of coating parameters for use in coating a second workpiece.

26. The computer-readable medium of claim 25, further comprising repeating (c) – (f) for subsequent workpieces in the series until the identified set of discrepancies falls within a selected tolerance.

27. A method in a computing system for automatically configuring parameters controlling operation of a deposition chamber to deposit material on each of a sequence of at least two wafers to improve conformity with a specified deposition pattern, comprising:

for each of the sequence of wafers, measuring thicknesses of the wafer before material is deposited on the wafer;

for each of the sequence of wafers, measuring thicknesses of the wafer after material is deposited on the wafer;

for each of the sequence of wafers after the first wafer of the sequence, configuring the parameters for depositing material on the wafer based on the specified deposition pattern, the measured thickness of the current wafer before material is deposited on the current wafer, the measured thickness of the previous wafer in the sequence before material is deposited on the previous wafer, the

parameters used for depositing material on the previous wafer, and the measured thicknesses of the previous wafer after material is deposited on the previous wafer.

28. The method of claim 27 wherein the specified deposition pattern is a flat deposition pattern.

29. The method of claim 27 wherein the specified deposition pattern is a concave deposition pattern.

30. The method of claim 27 wherein the specified deposition pattern is a convex deposition pattern.

31. The method of claim 27 wherein the specified deposition pattern is an arbitrary radial profile.

32. The method of claim 27 wherein the specified deposition pattern is an arbitrary profile.

33. The method of claim 27, further comprising, for a second deposition chamber:

retrieving a set of offset values characterizing differences between the deposition chamber and the second deposition chamber;

modifying the parameters most recently configured for the deposition chamber in accordance with the retrieved set of offset values to obtain a parameters for the second deposition chamber; and

configuring the second deposition chamber with the obtained parameters for the second deposition chamber.

34. An apparatus for automatically configuring parameters controlling operation of a deposition chamber to deposit material on each of a

sequence of wafers to improve conformity with a specified deposition pattern, comprising:

a pre-deposition measuring subsystem that measures thicknesses of each of the sequence of wafers before material is deposited on the wafer;

a post-deposition measuring subsystem that measures thicknesses of each of the sequence of wafers after material is deposited on the wafer;

a parameter configuration subsystem that configures the parameters for depositing material on each of the sequence of wafers after the first wafer of the sequence based on the specified deposition pattern, the measured thickness of the current wafer before material is deposited on the current wafer, the measured thickness of the previous wafer in the sequence before material is deposited on the previous wafer, the parameters used for depositing material on the previous wafer, and the measured thicknesses of the previous wafer after material is deposited on the previous wafer.

35. A method in a computing system for constructing a sensitivity matrix usable to adjust currents for a plurality of electrodes in an electroplating chamber to improve plating uniformity, comprising:

for each of a plurality of radii on the plating workpiece, obtaining a plating thickness on the workpiece at that radius when a set of baseline currents are delivered through the electrodes;

for each of the electrodes, for each of a plurality of plating workpiece radii, obtaining a plating thickness on the workpiece at that radius when the baseline currents are perturbed for that electrode; and

constructing a matrix, a first dimension of the matrix corresponding to the plurality of electrodes, a second dimension of the matrix corresponding to the plurality of radii, each entry for a particular electrode and a particular radius being determined by subtracting the thickness at that radius when the baseline currents are delivered through the electrodes from the thickness at that radius when the baseline

currents are perturbed for that electrode, then dividing by the magnitude by which that the current for that electrode was perturbed from its baseline current.

36. The method of claim 35 wherein the current for each electrode is perturbed by approximately +.05 amps.

37. The method of claim 35 wherein the current for each electrode is perturbed by a factor in the range between 1% and 10%.

38. The method of claim 35 wherein the obtained thicknesses are obtained by executing a simulation of the operation of the electroplating chamber based upon a mathematical model of the electroplating chamber.

39. The method of claim 35 wherein the obtained thicknesses are obtained by measuring workpieces plated in the electroplating chamber.

40. The method of claim 35, further comprising repeating the method to produce additional sensitivity matrices for a variety of different conditions.

41. The method of claim 35, further comprising using the constructed sensitivity matrix to modify for use in plating a second workpiece currents used to plate a first workpiece, such that the modified currents cause the second workpiece to be plated more uniformly than the first workpiece.

42. One or more computer memories collectively containing a sensitivity matrix data structure relating to a deposition chamber having a plurality of deposition initiators for depositing material on a workpiece having selected radii, a control parameter being associated with each of the deposition initiators, the data structure comprising a plurality of quantitative entries, each of the entries

predicting, for a given change in the control parameter associated with a given deposition initiator, the expected change in deposited material thickness at a given radius,

such that the contents of the data structure may be used to determine revised deposition initiator parameters for better conforming deposited material thicknesses to a target profile for deposited material thicknesses.

43. The computer memories of claim 42 wherein the deposition initiators are electrodes, and wherein the control parameters associated with the deposition initiators are currents delivered through the electrodes.

44. The computer memories of claim 42 wherein the sensitivity matrix data structure is a Jacobian sensitivity matrix.

45. The computer memories of claim 42 wherein the computer memories contain multiple sensitivity matrix data structures, each adapted to a different set of conditions.

46. One or more computer memories collectively containing a data structure for controlling a material deposition process, comprising a set of parameter values used in the material deposition process, the parameters having been generated by adjusting an earlier-used set of parameters to resolve differences between measurements of a workpiece deposited using the earlier-used set of parameters and a target deposition profile specified for the deposition process,

such that the contents of the data structure may be used to deposit an additional workpiece in greater conformance with the specified deposition profile.

47. The computer memories of claim 46 wherein the deposition process utilizes a plurality of electrodes, and wherein each parameter value of the set is an amount of current to be delivered through one of the plurality of electrodes.

48. One or more computer memories collectively containing a deposition chamber offset data structure, comprising a set of values indicating how to adjust a first parameter set used to obtain acceptable deposition results in a first deposition chamber to produce a second parameter set usable to obtain acceptable deposition results in a second deposition chamber.

49. A reactor for electrochemically processing a microelectronic workpiece comprising:

a fluid chamber configured to contain an electrochemical processing fluid;

a plurality of electrodes in the fluid chamber;

a workpiece holder positionable to hold the microelectronic workpiece in the fluid chamber;

an electrical power supply connected to the surface of the microelectronic workpiece and to the plurality of electrodes, at least two of the plurality of electrodes being independently connected to the electrical power supply to facilitate independent supply of power thereto; and

a control system connected to the electrical power supply to control at least one electrical power parameter respectively associated with each of the independently connected electrodes, the control system setting the at least one electrical power parameter for a given one of the independently connected electrodes based on one or more inputted parameters and a plurality of predetermined sensitivity values, the predetermined sensitivity values corresponding to process perturbations resulting from perturbations of the electrical power parameter for the given one of the independently connected electrodes.

50. The reactor of claim 49 wherein the at least one electrical parameter is electrical current.

51. The reactor of claim 49 wherein the sensitivity values are logically arranged within the control system as one or more Jacobian matrices.

52. The reactor of claim 49 wherein the at least one user input parameter comprises the thickness of a film that is to be electrochemically deposited on the at least one surface of the microelectronic workpiece.

53. The reactor of claim 49 wherein the independently connected electrodes are arranged concentrically with respect to one another.

54. The reactor of claim 49 wherein the independently connected electrodes are disposed at the same effective distance from the microelectronic workpiece.

55. The reactor of claim 54 wherein the independently connected electrodes are arranged concentrically with respect to one another.

56. The reactor of claim 49 wherein at least two of the independently connected electrodes are disposed at different effective distances from the surface of the microelectronic workpiece.

57. The reactor of claim 56 wherein the independently connected electrodes are arranged concentrically with respect to one another.

58. The reactor of claim 57 wherein the independently connected electrodes are arranged at increasing distances from the microelectronic workpiece from an outermost one of the plurality of concentric anodes to an innermost one of the independently connected electrodes.

59. The reactor of claim 49 wherein one or more of the independently connected electrodes is a virtual electrode.

60. A method in a computing system for controlling an electroplating process having multiple steps in an electroplating chamber having a plurality of electrodes, comprising:

for each electrode, determining the net plating charge delivered through the electrode during a first plating cycle to plate a first workpiece by summing the plating charges delivered through the electrode in each step of the process;

comparing a plating profile achieved in plating the first workpiece to a target plating profile to identify deviations between the achieved plating profile and the target plating profile;

determining new net plating charges for each electrode selected to reduce the identified deviations in a second workpiece;

for each new plating charge, distributing the new net plating charge across the steps of the process;

using the distributed new net plating charges to determine a current for each electrode for each step of the process; and

conducting a second plating cycle to plate a second workpiece, using the currents determined for each electrode for each step.

61. The method of claim 60 wherein the new net plating charges are distributed uniformly across all of the steps of the process.

62. The method of claim 60 wherein the new net plating charges are distributed across the steps of the process by distributing differences between the new net plating charge and the delivered net plating charge to a single step of the process.

63. The method of claim 60 wherein the distributing includes distributing the new net plating charges to each of two or more phases of a selected one of the steps of the process.

64. The method of step 60, further comprising repeating the method to further reduce deviations between the achieved plating profile and the target plating profile.

65. The method of step 60 wherein a sensitivity matrix is used to determine the new net plating charges.

66. The method of step 60 wherein a different sensitivity matrix is used to determine a new net plating charge for each step of the process.

67. A method in a computer system for evaluating a design for an electroplating reactor, comprising:

applying to a set of initial electrode currents a mathematical model embodying the reactor design to determine a first resulting plating profile;

comparing the first resulting plating profile to a target plating profile to obtain a first difference;

applying a sensitivity technique to identify a set of revised electrode currents;

applying the mathematical model to the set of revised electrode currents to determine a second resulting plating profile;

comparing the second resulting plating profile to the target plating profile to obtain a second difference; and

evaluating the design based on the obtained second difference.

68. An apparatus for automatically selecting parameters for using in controlling operation of a deposition chamber to deposit material on a selected wafer to optimize conformity with a specified deposition pattern, comprising:

a measurement receiving subsystem that receives:

pre-deposition thicknesses of the selected wafer before material is deposited on the wafer;

post-deposition thicknesses of an already-deposited wafer after material is deposited on the already-deposited wafer; and

pre-deposition thicknesses of the already-deposited wafer before material is deposited on the wafer; and

a parameter selection subsystem that selects the parameters to be used to deposit material on the selected wafer based on the specified deposition pattern, the pre-deposition thicknesses of the selected wafer, the pre-deposition thicknesses of the already-deposited wafer, parameters used for depositing material on the already-deposited wafer, and the post-deposition thicknesses of the already-deposited wafer.

69. The apparatus of claim 68, further comprising a deposition chamber for depositing material on the selected wafer using the parameters selected by the parameter selection subsystem.

70. The apparatus of claim 68, further comprising a memory containing a sensitivity matrix used by the parameter selection subsystem in selecting parameters to be used to deposit material on the selected wafer.

71. A method in a computing system for automatically configuring parameters usable to control operation of a deposition chamber to deposit material on a selected wafer to optimize conformity with a specified deposition pattern, comprising:

receiving pre-deposition thicknesses of the selected wafer before material is deposited on the wafer;

receiving post-deposition thicknesses of an already-deposited wafer after material is deposited on the already-deposited wafer; and

receiving pre-deposition thicknesses of the already-deposited wafer before material is deposited on the wafer;

selecting the parameters to be used to deposit material on the selected wafer based on the specified deposition pattern, the pre-deposition thicknesses of the selected wafer, the pre-deposition thicknesses of the already-deposited wafer, parameters used for depositing material on the already-deposited wafer, and the post-deposition thicknesses of the already-deposited wafer.

72. The method of claim 71, further comprising controlling a deposition chamber to deposit material on the selected wafer using the selected parameters.

73. The method of claim 71 wherein a sensitivity matrix is used in selecting parameters to be used to deposit material on the selected wafer.

74. A reactor for electrochemically processing a microelectronic workpiece comprising:

a fluid chamber configured to contain an electrochemical processing fluid;

a plurality of electrodes in the fluid chamber;

a workpiece holder positionable to hold the microelectronic workpiece in the fluid chamber; and

an electrical power supply connected to the surface of the microelectronic workpiece and to the plurality of electrodes, at least two of the plurality of electrodes being independently connected to the electrical power supply to facilitate independent supply of power thereto, the power supply configured to provide power to each independently connected electrode in accordance with an electrical power parameter provided for the independently connected electrode, each electrical power parameter being based on one or more inputted parameters and a plurality of predetermined sensitivity values, the predetermined sensitivity values corresponding to process perturbations resulting from perturbations of the electrical power parameter for the given one of the independently connected electrodes.

75. The reactor of claim 74 wherein each electrical power parameter is a current level.

76. The reactor of claim 74, further comprising an electrical power parameter selection subsystem that selects the electrical power parameter corresponding to each independently connected electrode.

77. An method for electroplating a selected surface using a plurality of electrodes, comprising:

obtaining a current specification set comprised of a plurality of current levels each specified for a particular one of the plurality of electrodes, the current levels of the current specification set comprising a modification of current levels of a distinguished current specification set in order to improve results produced by electroplating in accordance with the distinguished current specification set; and

for each electrode, delivering the current level specified for the electrode by the current specification set to the electrode in order to electroplate the selected surface.

78. The method of claim 77 wherein the current specification set is obtained by receiving it via an interface.

79. The method of claim 78 wherein the interface is a user interface.

80. The method of claim 78 wherein the interface is a removable media drive.

81. The method of claim 78 wherein the interface is a network connection.

82. The method of claim 77 wherein the current specification set is obtained by modifying the distinguished current specification set.

83. A method for processing a microelectronic workpiece, comprising:

(a) applying a seed layer to the workpiece using a physical vapor deposition process;

(b) measuring non-uniformity of the applied seed layer using a metrology device;

(c) correcting the measured non-uniformity of the applied seed layer in an multiple-electrode reactor whose electrodes are operated in accordance with electrical parameters determined based on the measured non-uniformity of the applied seed layer and characteristics of the multiple-electrode reactor.

84. The method of claim 83, further comprising, after (c):

(d) subjecting the workpiece to an electroless ion plating process in order to enhance the seed layer.

85. The method of claim 84, further comprising, after (d):

measuring the thickness of the enhanced seed layer using a metrology device; and

depositing a bulk metal layer atop the seed layer in an multiple-electrode reactor whose electrodes are operated in accordance with electrical parameters determined based on the measured thickness of the enhanced seed layer and characteristics of the multiple-electrode reactor.

86. A method for processing microelectronic workpieces, comprising:

(a) applying a seed layer to a first workpiece using a first physical vapor deposition tool;

(b) applying a seed layer to a second workpiece using a second physical vapor deposition tool;

(c) measuring non-uniformity of the seed layer applied to the first workpiece using a metrology device;

(d) measuring non-uniformity of the seed layer applied to the second workpiece using a metrology device;

(e) correcting the measured non-uniformity of the seed layer applied to the first workpiece in a first multiple-electrode reactor whose electrodes are operated in accordance with electrical parameters determined based on the measured non-uniformity of the seed layer applied to the first workpiece and characteristics of the first multiple-electrode reactor

(f) correcting the measured non-uniformity of the seed layer applied to the second workpiece in a second multiple-electrode reactor whose electrodes are operated in accordance with electrical parameters determined based on the measured non-uniformity of the seed layer applied to the second workpiece and characteristics of the second multiple-electrode reactor.

87. The method of claim 86, further comprising, after (f):

measuring the thickness of the corrected seed layer of the first workpiece using a metrology device;

depositing a bulk metal layer atop the seed layer of the first workpiece in a third multiple-electrode reactor whose electrodes are operated in accordance with electrical parameters determined based on the measured thickness of the corrected seed layer of the first workpiece and characteristics of the third multiple-electrode reactor;

measuring the thickness of the corrected seed layer of the second workpiece using a metrology device;

depositing a bulk metal layer atop the seed layer of the second workpiece in a third multiple-electrode reactor whose electrodes are operated in accordance with electrical parameters determined based on the measured thickness of the corrected seed layer of the second workpiece and characteristics of the third multiple-electrode reactor.

88. A method for constructing a library of deposition process parameter sets for use in controlling a material deposition tool in which multiple control points are controlled in order to control material deposition, comprising:

receiving a plurality of recipes, each recipe identifying a different set of characteristics to be used in performing a deposition process with the tool;

for each received recipe,

operating the tool in accordance with the recipe, and controlling each of the control points in accordance with an initial parameter set, to deposit a test workpiece;

evaluating the deposited test workpiece;

identifying deviations between the evaluation of the deposited test workpiece and a target deposition profile;

modifying the initial parameter set in a manner projected to reduce the identified deviations; and

storing the modified initial parameter set in a manner that associates it with the received recipe.

89. The method of claim 88, further comprising:

selecting one of the plurality of recipes;

in response to the recipe selection, retrieving the parameter set associated with the selected recipe; and

operating the tool in accordance with the selected recipe, and controlling each of the control points in accordance with the retrieved parameter set, to deposit a workpiece.

90. The method of claim 88 wherein the control points of the deposition tool are electrodes, and wherein each initial and modified parameter set specifies a manner of controlling each of the electrodes.

91. One or more computer memories collectively containing a plurality of deposition process parameter sets for use in controlling a material deposition tool in which multiple control points are controlled in order to control material deposition, each parameter set being associated with a processing recipe and containing a parameters specifying how to control each of the control points when performing the processing recipe.

92. The computer memories of claim 91 wherein the parameter sets are determined experimentally under computer control.

93. A method for performing material deposition on a workpiece, comprising:

selecting one of a plurality of processing recipes;

in response to the recipe selection, from a plurality of deposition process parameter sets determined experimentally under computer control, retrieving a parameter set associated with the selected recipe; and

operating a deposition tool in accordance with the selected recipe, and controlling each of a plurality of control points of the tool in accordance with the retrieved parameter set, to deposit a workpiece.

94. One or more computer memories collectively containing an electroplating current data structure, the data structure comprising information specifying, for each of a plurality of seed layer resistivity ranges, a set of currents to be delivered to a group of electrodes in order to electroplate a workpiece having a seed layer whose resistivity falls within the range.

95. The computer memories of claim 94 wherein the sets of currents specified by information in the data structure are experimentally determined under computer control.

96. A method in a computing system for automatically configuring parameters usable to control operation of a reaction chamber to electropolish a selected wafer to optimize conformity with a specified electropolishing pattern, comprising:

receiving pre-polishing thicknesses of the selected wafer before the selected wafer is polished;

receiving post-polishing thicknesses of an already-polished wafer after the already-polished wafer is polished; and

receiving pre-polishing thicknesses of the already-polished wafer before the already-polished wafer is polished;

selecting the parameters to be used to polish the selected wafer based on the specified polishing pattern, the pre-polishing thicknesses of the selected wafer, the pre-polishing thicknesses of the already-polished wafer, parameters used

for polishing the already-polished wafer, and the post-polishing thicknesses of the already-polished wafer.

97. A method in a computing system for determining deposition parameters to use in performing material deposition on a workpiece, comprising:

receiving thickness measurements at predetermined locations on the workpiece;

receiving a deposition profile specifying the pattern in which material is to be deposited on the workpiece;

obtaining a starting set of deposition parameters, a starting set of pre-deposition thickness measurements, and a starting set of deposited thicknesses corresponding to the starting sets of deposition parameters and pre-deposition thickness measurements;

based upon the received and obtained information, determining a set of deposition parameters to use in performing material deposition on the workpiece.

98. The method of claim 97 wherein the set of deposition parameters to use in performing material deposition on the workpiece is determined using sensitivity techniques.

99. A method in a computing system for electroplating a microelectronic workpiece, comprising:

receiving data representing a profile of a seed layer that has been applied to the workpiece;

identifying deficiencies in the seed layer based upon the profile of the seed layer represented by the received data;

determining a set of control parameters for plating the workpiece in a manner that compensates for the identified deficiencies in the seed layer; and

communicating the determined set of control parameters to a plating tool for use in plating the workpiece.

100. The method of claim 99 wherein the determined set of control parameters is, for each of a plurality of electrodes of the plating tool, one or more current levels to be delivered through the electrode.

101. A processing container for electrochemically processing a microelectronic workpiece comprising:

a principal fluid flow chamber;

a plurality of concentric anodes disposed at different elevations in the principal fluid flow chamber so as to place the concentric anodes at different distances from a microelectronic workpiece under process; and

a controller configured to deliver through each of the concentric anodes a current that is (a) based upon a current delivered through the concentric anode to process an earlier-processed microelectronic workpiece and (b) selected to produce a more uniform processing of the workpiece under process than the processing of the earlier-processed microelectronic workpiece.

102. The processing container of claim 101 wherein the plurality of concentric anodes are arranged at increasing distances from the microelectronic workpiece from an outermost one of the plurality of concentric anodes to an innermost one of the plurality of concentric anodes.

103. The processing container of claim 102 wherein the principal fluid flow chamber is defined at an upper portion thereof by an angled wall, the angled wall supporting one or more of the plurality of concentric anodes.

104. The processing container of claim 101 wherein one or more of the plurality of concentric anodes is a virtual anode.

105. The processing container of claim 104 wherein the virtual anode comprises:

an anode chamber housing having a processing fluid inlet and a processing fluid outlet, the processing fluid outlet being disposed in close proximity to the microelectronic workpiece under process; and

at least one conductive anode element disposed in the anode chamber housing.

106. The processing container of claim 104 wherein the at least one conductive anode element is formed from an inert material.

107. The processing container of claim 101 and further comprising a plurality of nozzles disposed to provide a flow of the electrochemical processing fluid to the principal fluid flow chamber, the plurality of nozzles being arranged and directed to provide vertical and radial fluid flow components that combine to generate a substantially uniform normal flow component radially across the at least one surface of the workpiece.

108. The processing container of claim 101 wherein the principal fluid flow chamber is defined at an upper portion thereof by an angled wall, the angled wall supporting one or more of the plurality of concentric anodes.

109. The processing container of claim 101 wherein the principal fluid flow chamber further comprises an inlet disposed at a lower portion thereof that is configured to provide a Venturi effect that facilitates recirculation of processing fluid flow in a lower portion of the principal fluid flow chamber.

110. The processing container of claim 101, further comprising a current optimization subsystem for selecting the currents delivered through the concentric anodes by the controller.

111. The processing container of claim 110, further comprising a memory containing a Jacobian sensitivity matrix reflecting characteristics of the principal fluid flow chamber used by the current optimization subsystem in selecting the currents delivered through the concentric anodes by the controller.

112. The processing container of claim 101, further comprising a pump for circulating processing fluid within the principal flow chamber.

113. The processing container of claim 101 wherein the fluid flow chamber is adapted to contain an electrolyte solution for electroplating the microelectronic workpiece.

114. The processing container of claim 113 wherein the current delivered by the controller to each anode is selected to produce a more uniform layer of electroplated material on the microelectronic workpiece under process than was produced on the earlier-processed microelectronic workpiece.

115. A method for electroplating a material on a microelectronic workpiece comprising:

introducing at least one surface of the microelectronic workpiece into an electroplating bath;

providing a plurality of anodes in the electroplating bath, the plurality of anodes being spaced at different distances from the at least one surface of the microelectronic workpiece that is to be electroplated; and

for each of the plurality of anodes, inducing an electrical current between the anode and the at least one surface of the microelectronic workpiece, the induced electrical current being (a) based on an electrical current induced between the anode and a previously electroplated microelectronic workpiece and (b) selected to improve on an electroplating result achieved for the previously electroplated microelectronic workpiece.

116. A method of claim 115 wherein each of the plurality of anodes is provided with a fixed electrical current over a substantial portion of the electroplating process.

117. The method of claim 115 and further comprising the step of providing a substantially uniform normal flow of electroplating solution to the at least one surface of the microelectronic workpiece.

118. The method of claim 115 and further comprising the step of providing a substantially uniform normal flow of electroplating solution to the at least one surface of the microelectronic workpiece without an intermediate diffuser disposed between the plurality of anodes and the at least one surface of the microelectronic workpiece.

119. The method of claim 115 wherein each induced electrical current is selected to improve on a level of plating uniformly achieved for the previously electroplated microelectronic workpiece.

120. The method of claim 115 wherein each induced electrical current is selected to improve compliance of a plating profile achieved for the previously electroplated microelectronic workpiece with a target plating profile.

121. The method of step 115, further comprising selecting the induced electric currents.

122. The method of claim 121, further comprising performing a sensitivity analysis of the electroplating that is a basis for selecting the induced electric currents.

123. A reactor for electrochemically processing a microelectronic workpiece comprising:

a principal fluid flow chamber;

a plurality of electrodes disposed in the principal fluid flow chamber;

a workpiece holder positioned to hold at least one surface of the microelectronic workpiece in contact with an electrochemical processing fluid in the principal fluid flow chamber at least during electrochemical processing of the microelectronic workpiece;

one or more electrical contacts connected to electrically contact the at least one surface of the microelectronic workpiece;

an electrical power supply connected to the one or more electrical contacts and to the plurality of electrodes, at least two of the plurality of electrodes being independently connected to the electrical power supply to facilitate independent supply of power thereto;

a control system connected to the electrical power supply to control at least one electrical power parameter respectively associated with each of the independently connected electrodes, the control system setting the at least one electrical power parameter for a given one of the independently connected electrodes based on one or more user input parameters and a plurality of predetermined sensitivity values, the predetermined sensitivity values corresponding to process perturbations resulting from perturbations of the electrical power parameter for the given one of the independently connected electrodes.

124. A reactor as claimed in claim 123 wherein the at least one electrical parameter is electrical current.

125. A reactor as claimed in claim 123 wherein the sensitivity values are logically arranged within the control system as one or more Jacobian matrices.

126. A reactor as claimed in claim 123 wherein the at least one user input parameter comprises the thickness of a film that is to be electrochemically deposited on the at least one surface of the microelectronic workpiece.

127. A reactor as claimed in claim 123 wherein at least two of the independently connected electrodes are disposed at different effective distances from the surface of the microelectronic workpiece.

128. A reactor as claimed in claim 123 wherein the independently connected electrodes are arranged concentrically with respect to one another.

129. A reactor as claimed in claim 123 wherein the independently connected electrodes are disposed at the same effective distance from the at least one surface of the microelectronic workpiece.

130. A reactor as claimed in claim 129 wherein the independently connected electrodes are arranged concentrically with respect to one another.

131. A reactor as claimed in claim 127 wherein the independently connected electrodes are arranged concentrically with respect to one another.

132. A reactor as claimed in claim 131 wherein the independently connected electrodes are arranged at increasing distances from the at least one surface of the microelectronic workpiece from an outermost one of the plurality of concentric anodes to an innermost one of the independently connected electrodes.

133. A reactor as claimed in claim 123 wherein one or more of the independently connected electrodes is a virtual electrode.

134. A reactor as claimed in claim 133 wherein the virtual electrode comprises:

an electrode chamber housing having a processing fluid inlet and a processing fluid outlet, the processing fluid outlet being disposed in close proximity to the microelectronic workpiece under process;

at least one conductive electrode element disposed in the electrode chamber housing.

135. A processing container as claimed in claim 134 wherein the at least one conductive electrode element is formed from an inert material.

136. A processing container as claimed in claim 123 and further comprising a plurality of nozzles disposed to provide a flow of the electrochemical processing fluid to the principal fluid flow chamber, the plurality of nozzles being arranged and directed to provide vertical and radial fluid flow components that combine to generate a substantially uniform normal flow component radially across the at least one surface of the workpiece.

137. A reactor for immersion processing at least one surface of a microelectronic workpiece, the reactor comprising:

a reactor head including a workpiece support;

one or more electrical contacts disposed on the workpiece support and positioned thereon to make electrical contact with the microelectronic workpiece;

a processing container including a plurality of nozzles angularly disposed in a sidewall of a principal fluid flow chamber at a level within the principal fluid flow chamber below a surface of a bath of processing fluid normally contained therein during immersion processing;

a plurality of individually operable electrical conductors disposed in the principal fluid flow chamber and positioned for electrical contact with the processing fluid.

138. A reactor as claimed in claim 137 and further comprising an electrode disposed at a lower portion of the processing container to provide electrical contact between an electrical power supply and the processing fluid.

139. A reactor as claimed in claim 138 wherein the processing container is defined at an upper portion thereof by an angled wall, the processing container further comprising at least one further electrode in fixed positional alignment with the angled wall to provide electrical contact between an electrical power supply and the processing fluid.

140. A reactor as claimed in claim 137 and further comprising a motor connected to rotate the workpiece support and an associated microelectronic workpiece at least during processing of the at least one surface of the microelectronic workpiece.

141. A reactor for immersion processing of a microelectronic workpiece, the reactor comprising:

a processing container having a processing fluid inlet through which a processing fluid flows into the processing container, the processing container further having an upper rim forming a weir over which processing fluid flows to exit from processing container;

at least one helical flow chamber disposed exterior to the processing container to receive processing fluid exiting from the processing container over the weir.

142. A reactor as claimed in claim 141 wherein the helical flow chamber is disposed about and circumvents exterior sidewalls of the processing container.

143. A reactor as claimed in claim 142 wherein the processing container comprises one or more projections circumventing exterior sidewalls thereof that at least partially define the helical flow chamber.

144. A reactor as claimed in claim 143 wherein the reactor further comprises an outer container exterior to the processing container, interior sidewalls of the outer container cooperating with the one or more projections to define the helical flow chamber therebetween.

145. An apparatus for processing a microelectronic workpiece comprising:

a plurality of workpiece processing stations;

a microelectronic workpiece robotic transfer;

at least one of the plurality of workpiece processing stations including a reactor having a processing container comprising

a principal fluid flow chamber;

a plurality of nozzles angularly disposed in one or more sidewalls of the principal fluid flow chamber at a level within the principal fluid flow chamber below a surface of a bath of processing fluid normally contained therein during immersion processing.

146. An apparatus as claimed in claim 145 wherein the plurality of nozzles are disposed with respect to one another to provide vertical and radial fluid flow components that combine to generate a substantially uniform normal flow component radially across the at least one surface of the workpiece.

147. An apparatus as claimed in claim 145 wherein the plurality of nozzles are arranged so that the substantially uniform normal flow component is slightly greater at a radial central portion as referenced to the workpiece thereby forming a meniscus that assists in preventing air entrapment as the workpiece is

brought into engagement with the surface of the processing fluid in the processing container.

148. An apparatus as claimed in claim 145 wherein the processing container further comprises a vented antechamber upstream of the plurality of nozzles.

149. An apparatus as claimed in claim 148 wherein the processing container further comprises a plenum disposed between the vented antechamber and the plurality of nozzles.

150. An apparatus as claimed in claim 148 wherein the vented antechamber comprises an inlet portion and an outlet portion, the inlet portion having a smaller cross-section compared to the outlet portion.

151. An apparatus as claimed in claim 147 wherein at least some of the plurality of nozzles are generally horizontal slots in the one or more sidewalls of the principal fluid flow chamber.

152. An apparatus as claimed in claim 145 wherein the principal fluid flow chamber further comprises a Venturi effect inlet.

153. An apparatus as claimed in claim 151 wherein the Venturi effect inlet generates a Venturi effect that facilitates recirculation of processing fluid flow in a lower portion of the principal fluid flow chamber.

154. A processing container for providing a flow of a processing fluid during immersion processing of at least one surface of a microelectronic workpiece, the processing container comprising:

a principal fluid flow chamber;

a plurality of nozzles angularly disposed in one or more sidewalls of the principal fluid flow chamber at a level within the principal fluid flow chamber below a surface of a bath of processing fluid contained therein during immersion processing.

155. A microelectronic workpiece processing container as claimed in claim 154 wherein the plurality of nozzles are disposed in the one or more sidewalls of the principal fluid flow chamber so as to form a the substantially uniform normal flow component radially across the surface of the workpiece in which the substantially uniform normal flow component is slightly greater at a radial central portion thereby forming a meniscus that assists in preventing air entrapment as the workpiece is brought into engagement with the surface of the processing fluid in the processing container.

156. A microelectronic workpiece processing container as claimed in claim 152 and further comprising an antechamber upstream of the plurality of nozzles, the antechamber being dimensioned to assist in the removal of gaseous components entrained in the processing fluid.

157. A microelectronic workpiece processing container as claimed in claim 156 and further comprising a plenum disposed between the antechamber and the plurality of nozzles.

158. A microelectronic workpiece processing container as claimed in claim 154 wherein the antechamber comprises an inlet and an outlet, the inlet having a smaller cross-section compared to the outlet.

159. A microelectronic workpiece processing container as claimed in claim 154 wherein at least some of the plurality of nozzles are generally

horizontal slots disposed through the one or more sidewalls of the principal fluid flow chamber.

160. A processing container as claimed in claim 154 wherein the principal fluid flow chamber comprises one or more contoured sidewalls at an upper portion thereof to inhibit fluid flow separation as the processing fluid flows toward an upper portion of the principal fluid flow chamber to contact the surface of the microelectronic workpiece.

161. A processing container as claimed in claim 154 wherein the principal fluid flow chamber is defined at an upper portion thereof by an angled wall.

162. A microelectronic workpiece processing container as claimed in claim 154 wherein the principal fluid flow chamber further comprises a Venturi effect inlet disposed at a lower portion thereof.

163. A microelectronic workpiece processing container as claimed in claim 162 wherein the Venturi effect inlet is configured to provide a Venturi effect that facilitates recirculation of processing fluid flow in a lower portion of the principal fluid flow chamber.

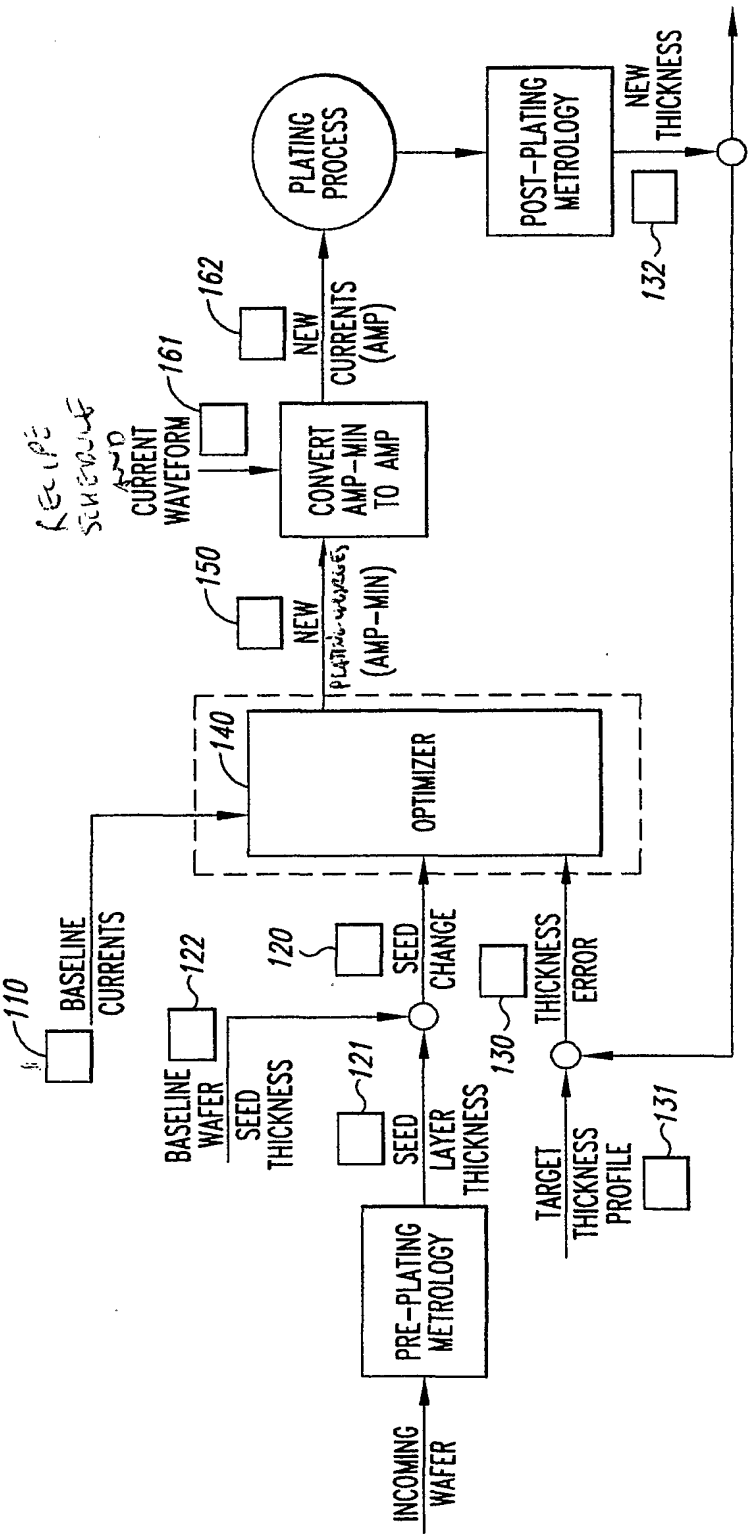

INCOMING WAFER
PRE-PLATING METROLOGY
BASELINE CURRENTS
110
BASELINE WAFER SEED THICKNESS
122
120
SEED LAYER THICKNESS
121
SEED CHANGE
130
THICKNESS ERROR
TARGET THICKNESS PROFILE
131
OPTIMIZER
140
NEW (AMP-MIN)
150
CONVERT AMP-MIN TO AMP
CURRENT WAVEFORM
161
NEW CURRENTS (AMP)
162
PLATING PROCESS
POST-PLATING METROLOGY
132
NEW THICKNESS

Fig. 1

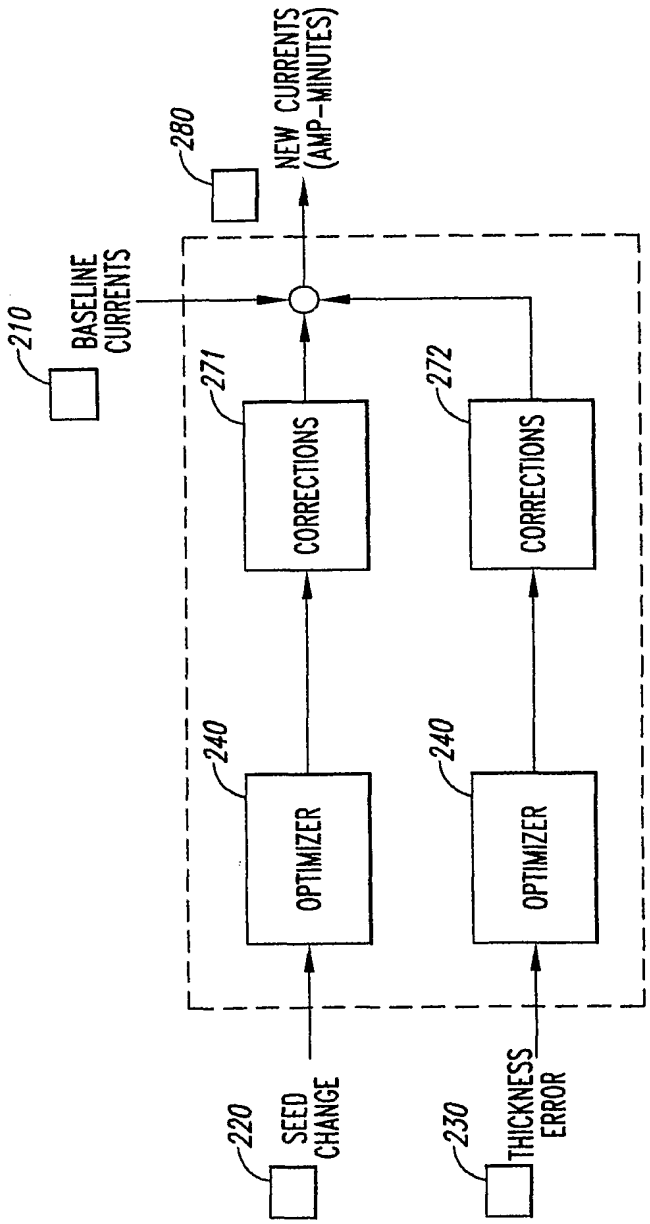

280
NEW CURRENTS (AMP-MINUTES)
210
BASELINE CURRENTS
271
CORRECTIONS
272
CORRECTIONS
240
OPTIMIZER
240
OPTIMIZER
220
SEED CHANGE
230
THICKNESS ERROR

Fig. 2

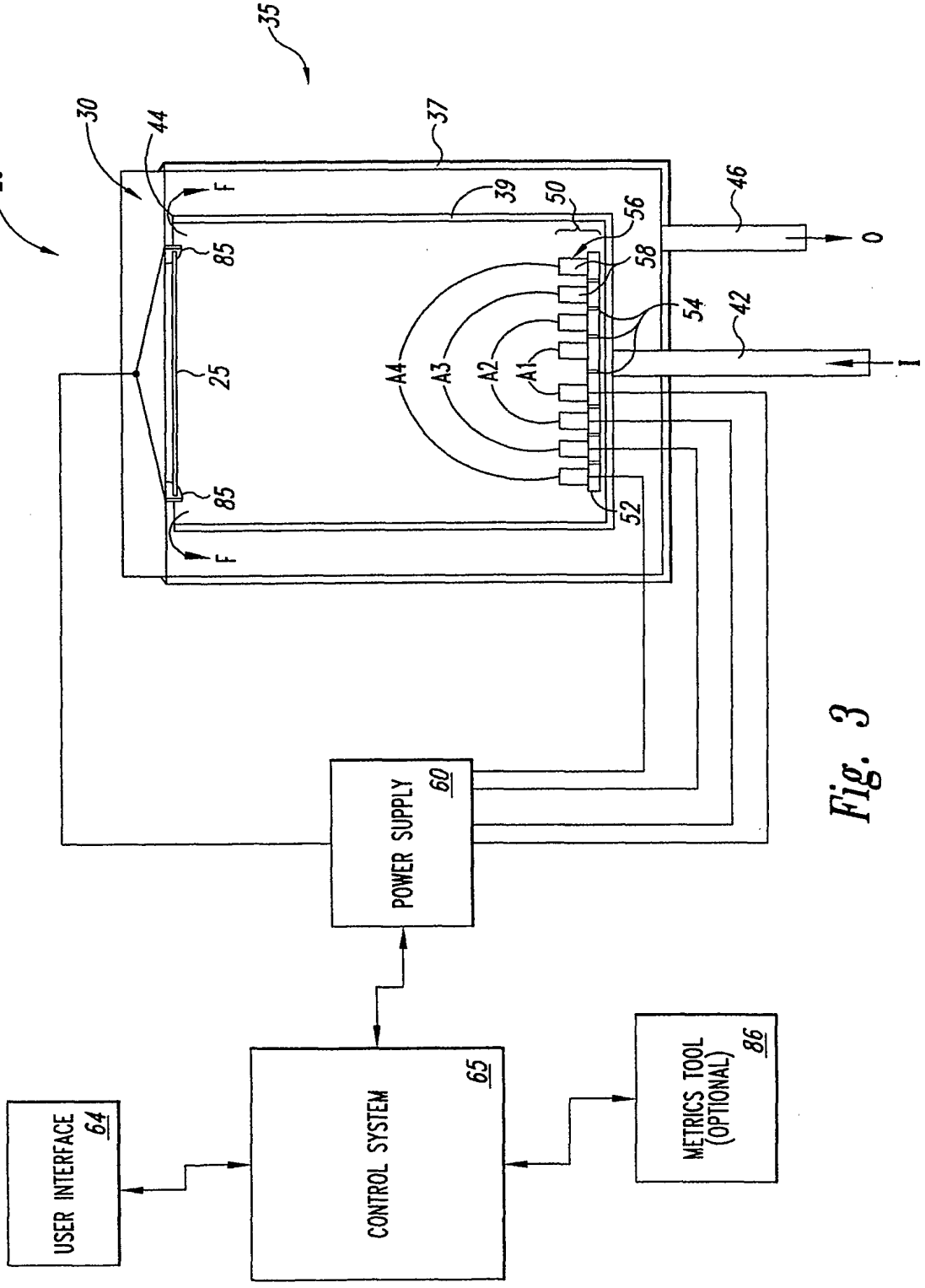

20
30
35
37
44
F
85
25
39
50
56
58
54
46
42
O
I
A4
A3
A2
A1
52
POWER SUPPLY
60
CONTROL SYSTEM
65
USER INTERFACE
64
METRICS TOOL
(OPTIONAL)
86

Fig. 3

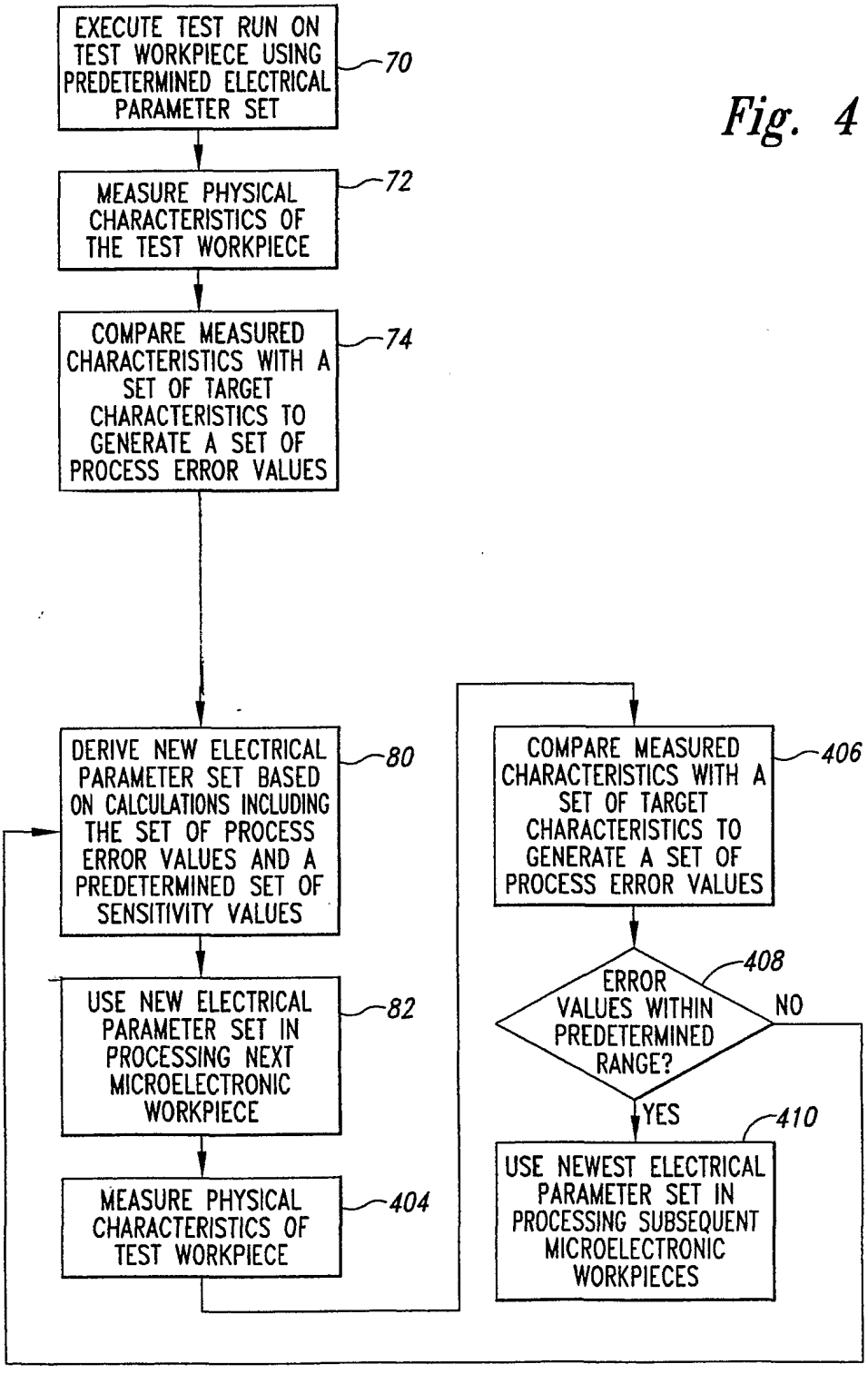

EXECUTE TEST RUN ON TEST WORKPIECE USING PREDETERMINED ELECTRICAL PARAMETER SET
70
MEASURE PHYSICAL CHARACTERISTICS OF THE TEST WORKPIECE
72
COMPARE MEASURED CHARACTERISTICS WITH A SET OF TARGET CHARACTERISTICS TO GENERATE A SET OF PROCESS ERROR VALUES
74
DERIVE NEW ELECTRICAL PARAMETER SET BASED ON CALCULATIONS INCLUDING THE SET OF PROCESS ERROR VALUES AND A PREDETERMINED SET OF SENSITIVITY VALUES
80
USE NEW ELECTRICAL PARAMETER SET IN PROCESSING NEXT MICROELECTRONIC WORKPIECE
82
MEASURE PHYSICAL CHARACTERISTICS OF TEST WORKPIECE
404
COMPARE MEASURED CHARACTERISTICS WITH A SET OF TARGET CHARACTERISTICS TO GENERATE A SET OF PROCESS ERROR VALUES
406
ERROR VALUES WITHIN PREDETERMINED RANGE?
408
NO
YES
USE NEWEST ELECTRICAL PARAMETER SET IN PROCESSING SUBSEQUENT MICROELECTRONIC WORKPIECES
410

Fig. 4

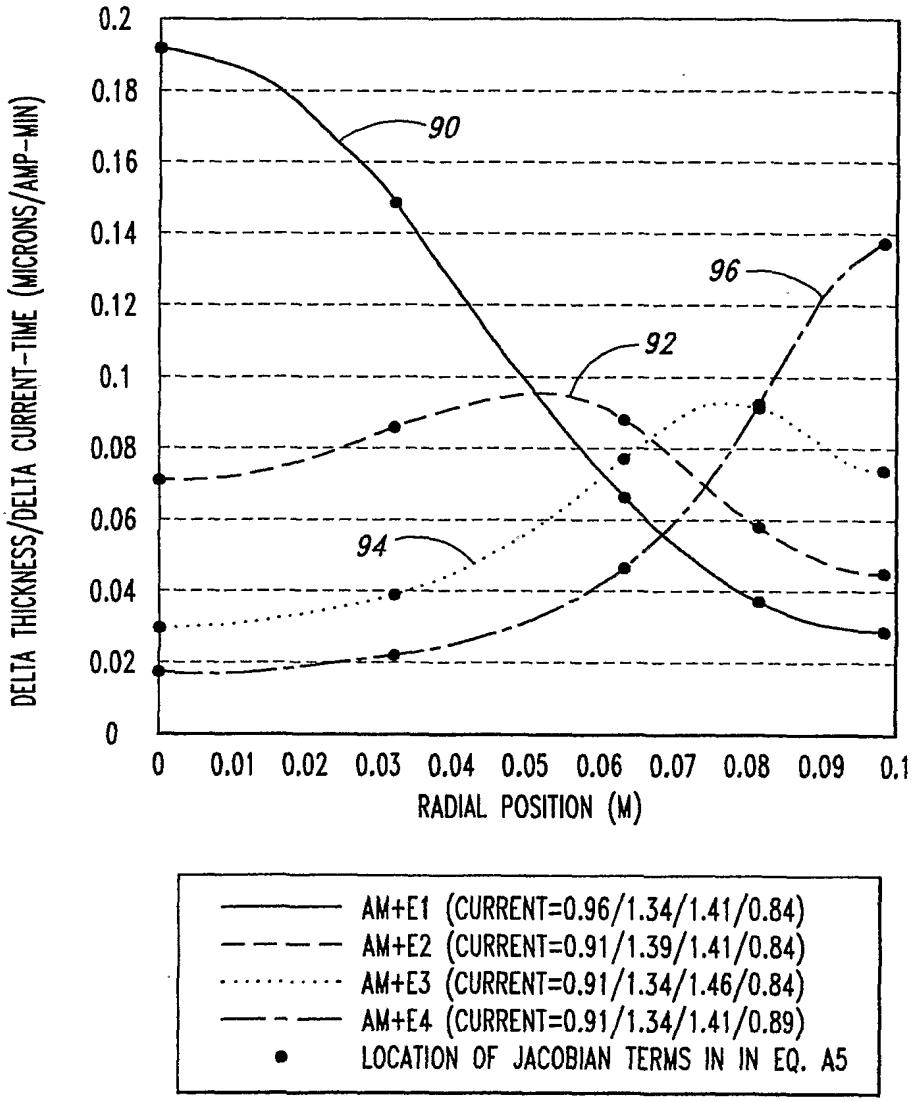

DELTA THICKNESS/DELTA CURRENT-TIME (MICRONS/AMP-MIN)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
RADIAL POSITION (M)
90
92
94
96
AM+E1 (CURRENT=0.96/1.34/1.41/0.84)
AM+E2 (CURRENT=0.91/1.39/1.41/0.84)
AM+E3 (CURRENT=0.91/1.34/1.46/0.84)
AM+E4 (CURRENT=0.91/1.34/1.41/0.89)
LOCATION OF JACOBIAN TERMS IN IN EQ. A5

Fig. 5

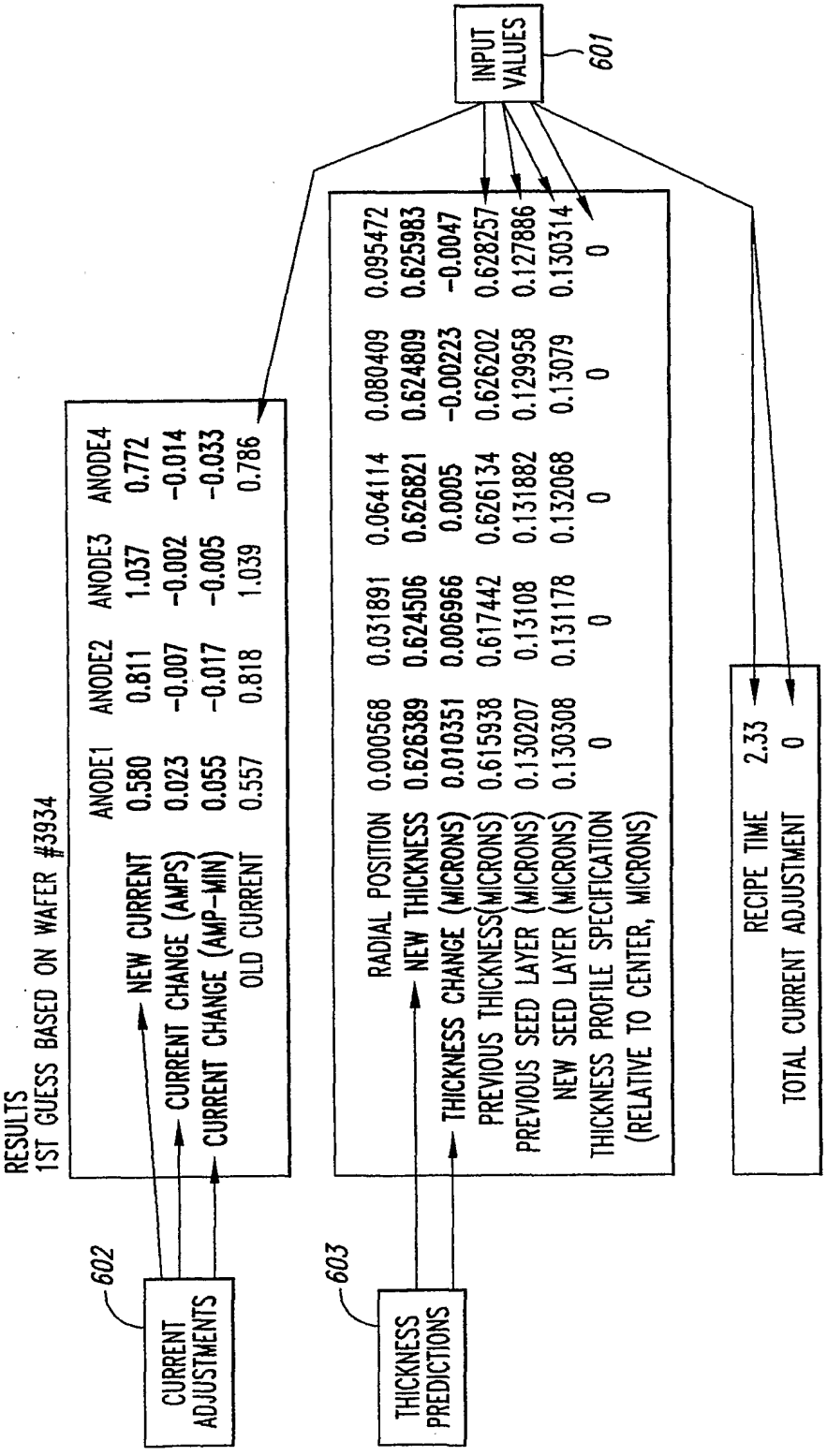

INPUT VALUES
601
RESULTS
1ST GUESS BASED ON WAFER #3934
ANODE1 ANODE2 ANODE3 ANODE4
NEW CURRENT 0.580 0.811 1.037 0.772
CURRENT CHANGE (AMPS) 0.023 -0.007 -0.002 -0.014
CURRENT CHANGE (AMP-MIN) 0.055 -0.017 -0.005 -0.033
OLD CURRENT 0.557 0.818 1.039 0.786
602
CURRENT ADJUSTMENTS
603
THICKNESS PREDICTIONS
RADIAL POSITION 0.000568 0.031891 0.064114 0.080409 0.095472
NEW THICKNESS 0.626389 0.624506 0.626821 0.624809 0.625983
THICKNESS CHANGE (MICRONS) 0.010351 0.006966 0.0005 -0.00223 -0.0047
PREVIOUS THICKNESS(MICRONS) 0.615938 0.617442 0.626134 0.626202 0.628257
PREVIOUS SEED LAYER (MICRONS) 0.130207 0.13108 0.131882 0.129958 0.127886
NEW SEED LAYER (MICRONS) 0.130308 0.131178 0.132068 0.13079 0.130314
THICKNESS PROFILE SPECIFICATION (RELATIVE TO CENTER, MICRONS) 0 0 0 0 0
RECIPE TIME 2.33
TOTAL CURRENT ADJUSTMENT 0

Fig. 6

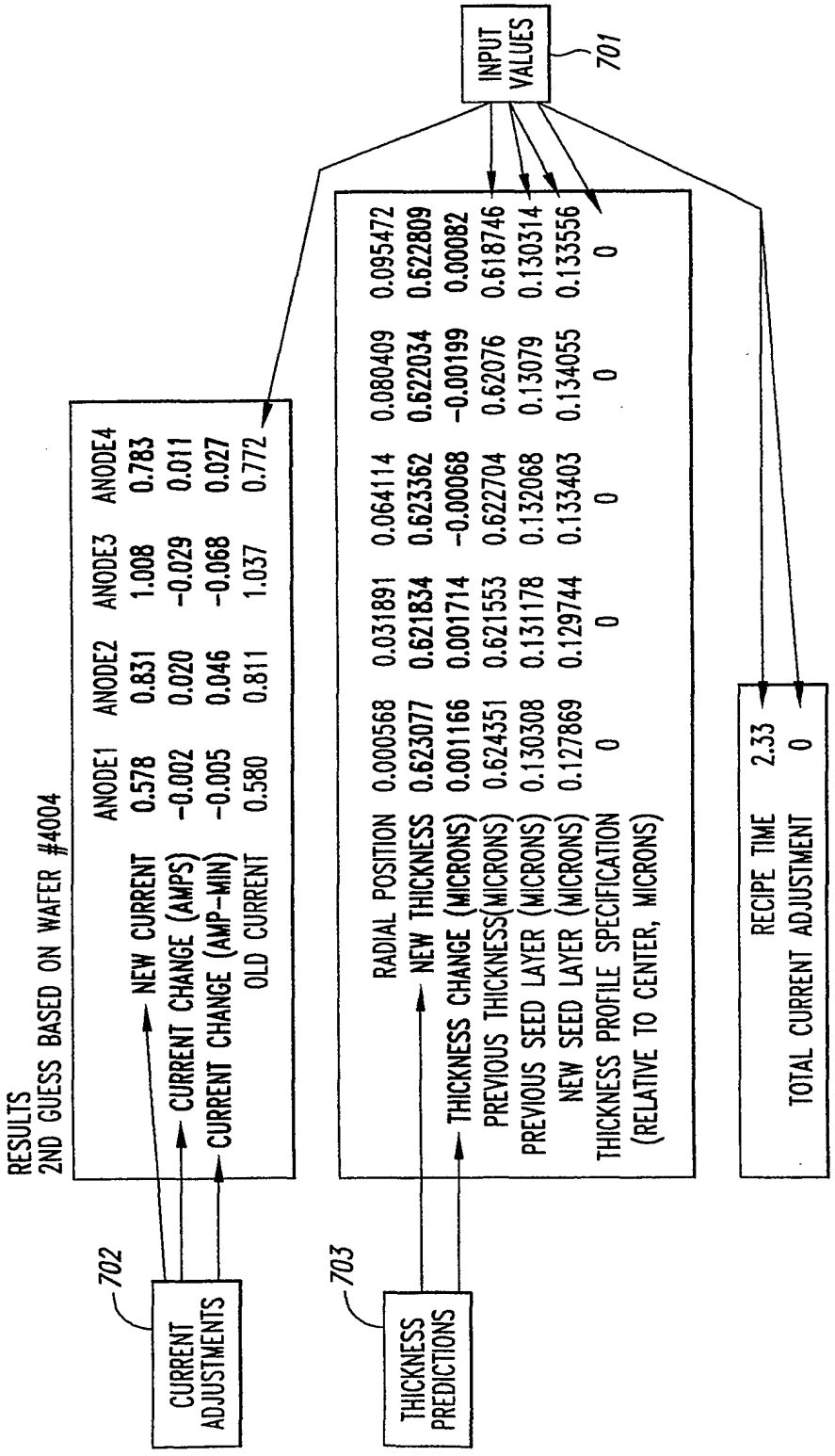

INPUT VALUES
701
RESULTS
2ND GUESS BASED ON WAFER #4004
ANODE1 ANODE2 ANODE3 ANODE4
NEW CURRENT 0.578 0.831 1.008 0.783
CURRENT CHANGE (AMPS) -0.002 0.020 -0.029 0.011
CURRENT CHANGE (AMP-MIN) -0.005 0.046 -0.068 0.027
OLD CURRENT 0.580 0.811 1.037 0.772
RADIAL POSITION 0.000568 0.031891 0.064114 0.080409 0.095472
NEW THICKNESS 0.623077 0.621834 0.623362 0.622034 0.622809
THICKNESS CHANGE (MICRONS) 0.001166 0.001714 -0.00068 -0.00199 0.00082
PREVIOUS THICKNESS(MICRONS) 0.624351 0.621553 0.622704 0.62076 0.618746
PREVIOUS SEED LAYER (MICRONS) 0.130308 0.131178 0.132068 0.13079 0.130314
NEW SEED LAYER (MICRONS) 0.127869 0.129744 0.133403 0.134055 0.133556
THICKNESS PROFILE SPECIFICATION (RELATIVE TO CENTER, MICRONS) 0 0 0 0 0
RECIPE TIME 2.33
TOTAL CURRENT ADJUSTMENT 0
702
CURRENT ADJUSTMENTS
703
THICKNESS PREDICTIONS

Fig. 7

FIGURE 9

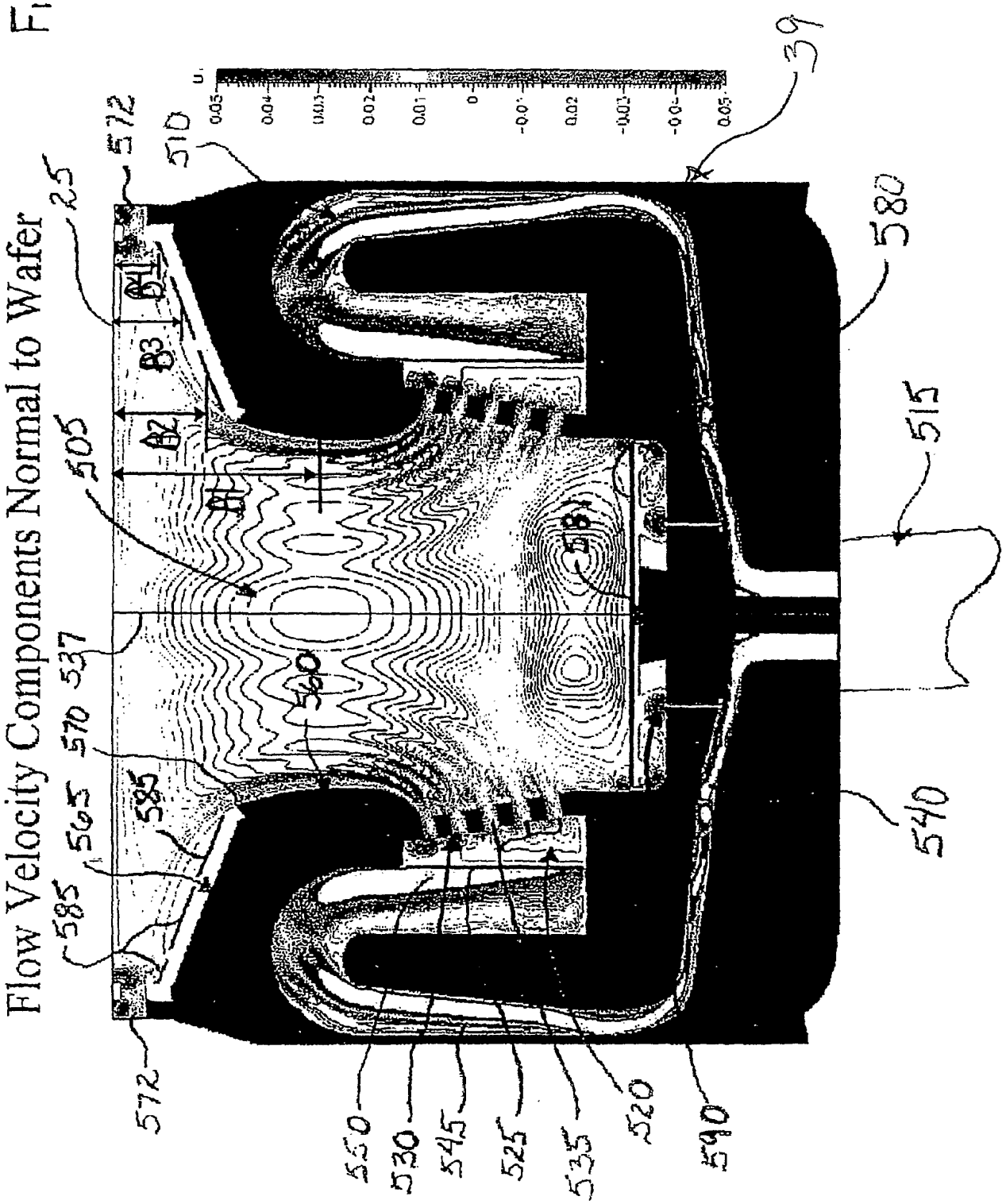
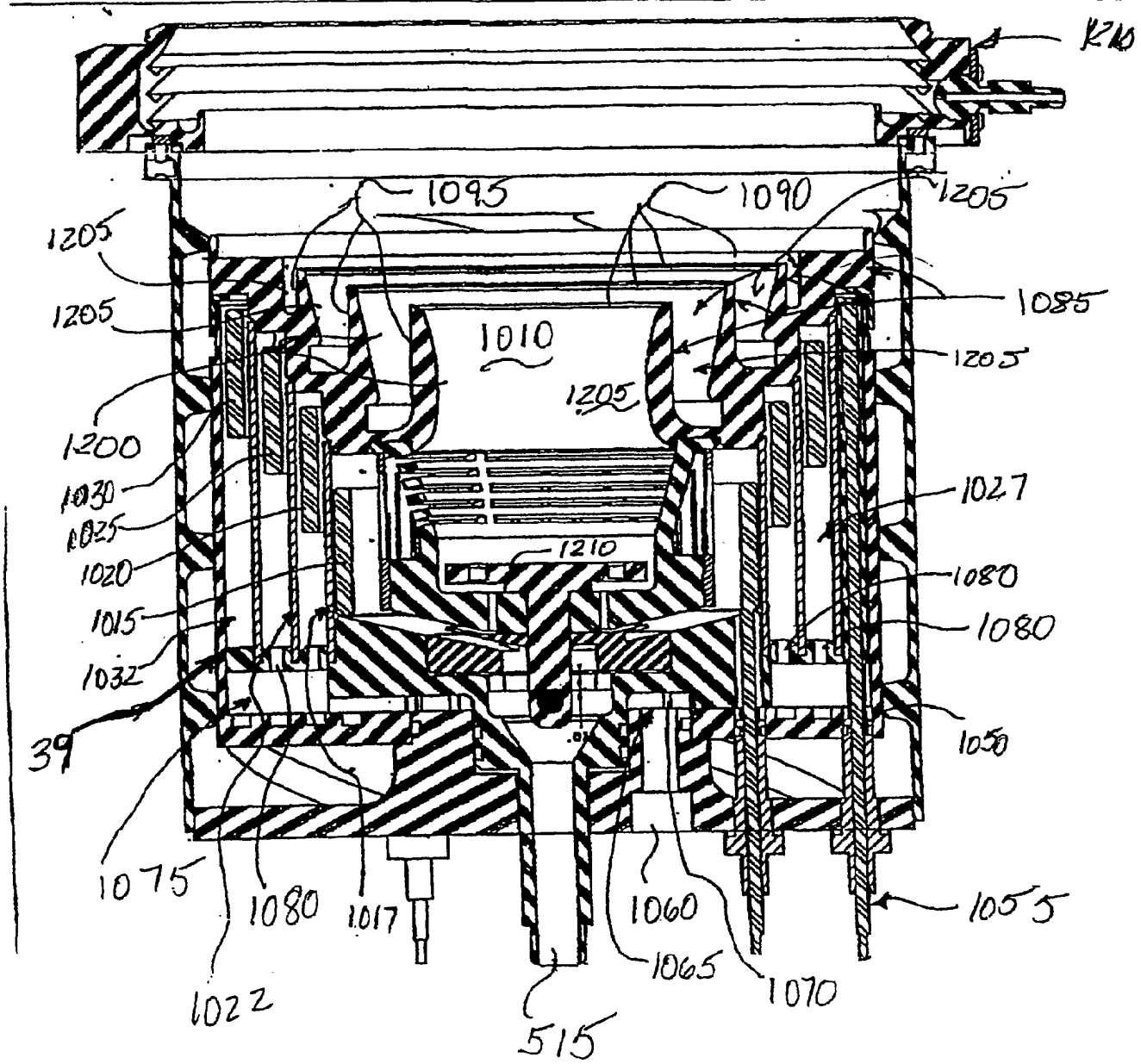

Flow Velocity Components Normal to Wafer
572
510
39
25
505
580
515
537
500
570
585
565
540
550
530
545
525
535
520
590
D1
D2
D3
B1
B2
B3

FIGURE 9


1095
1090
1205
1205
1205
1085
1010
1205
1205
1200
1030
1025
1020
1015
1032
39
1210
1027
1080
1080
1050
1075
1080
1017
1060
1065
1070
1055
1022
515

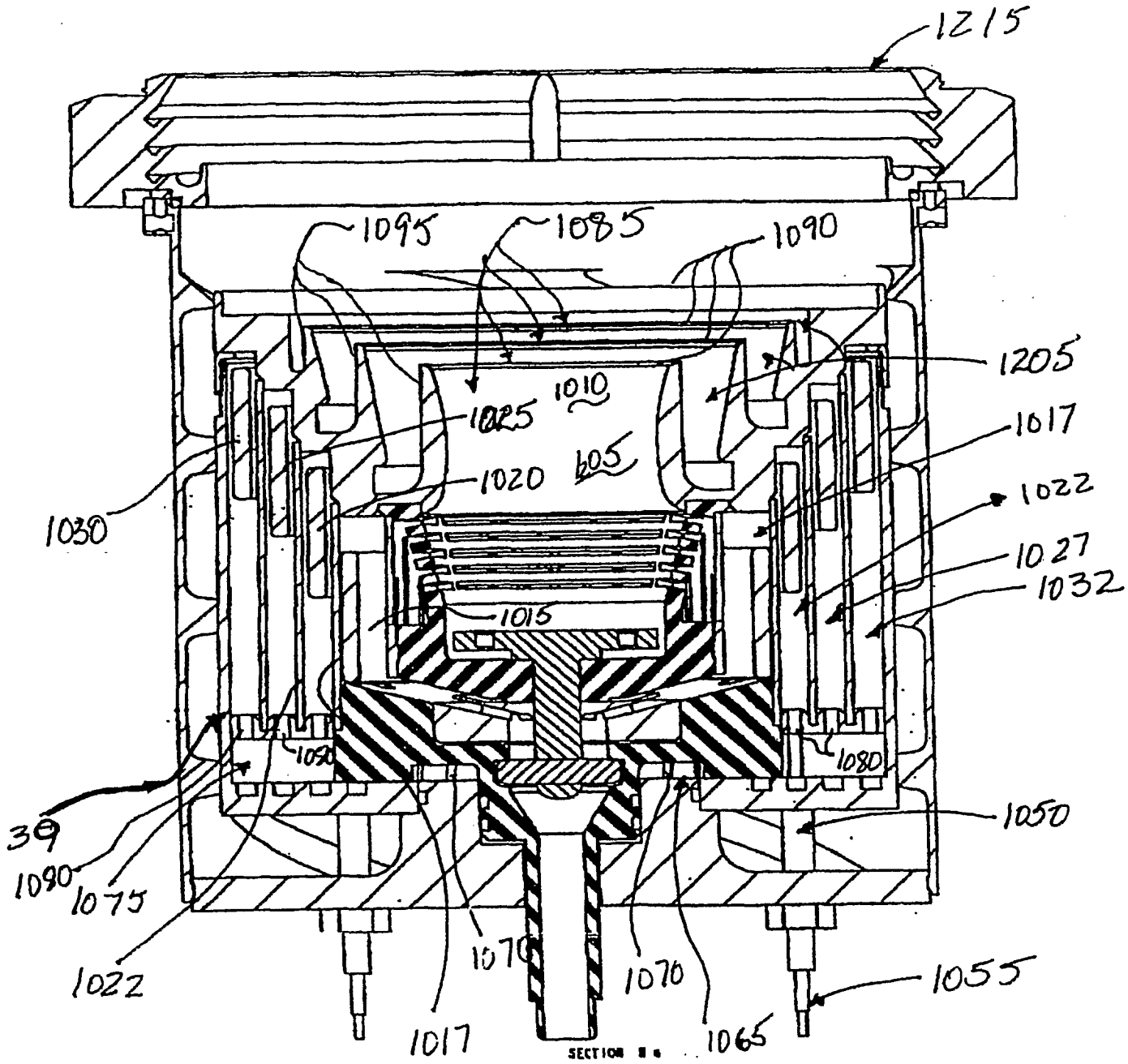

1215
1095
1085
1090
1205
1010
1025
1017
1020
605
1022
1030
1027
1032
1015
1080
1050
39
1090
1075
1070
1070
1055
1022
1017
1065
SECTION

FIGURE 10

FIGURE 11

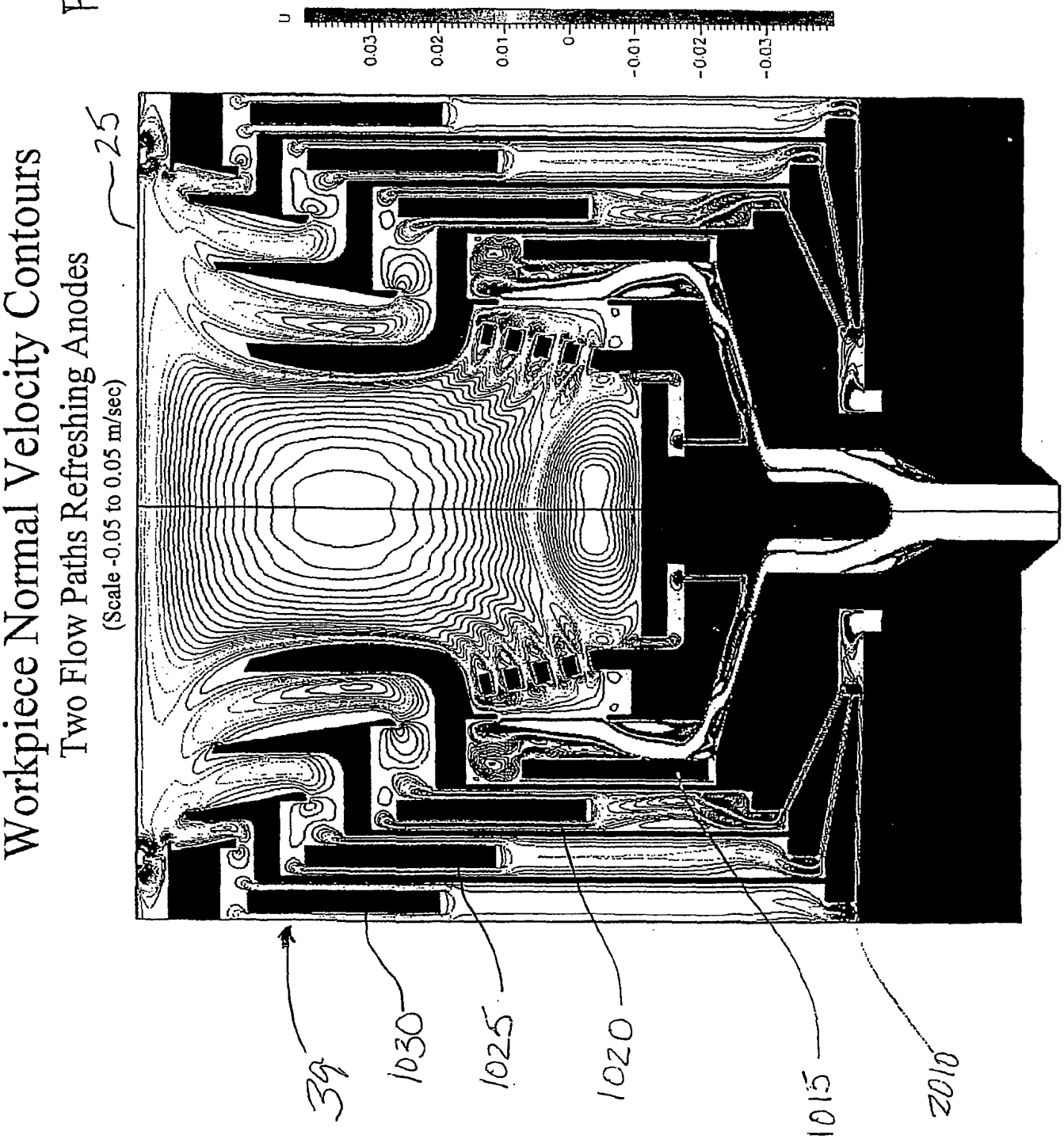

Workpiece Normal Velocity Contours
Two Flow Paths Refreshing Anodes
(Scale -0.05 to 0.05 m/sec)
25
U
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
39
1030
1025
1020
1015
2010

FIGURE 12

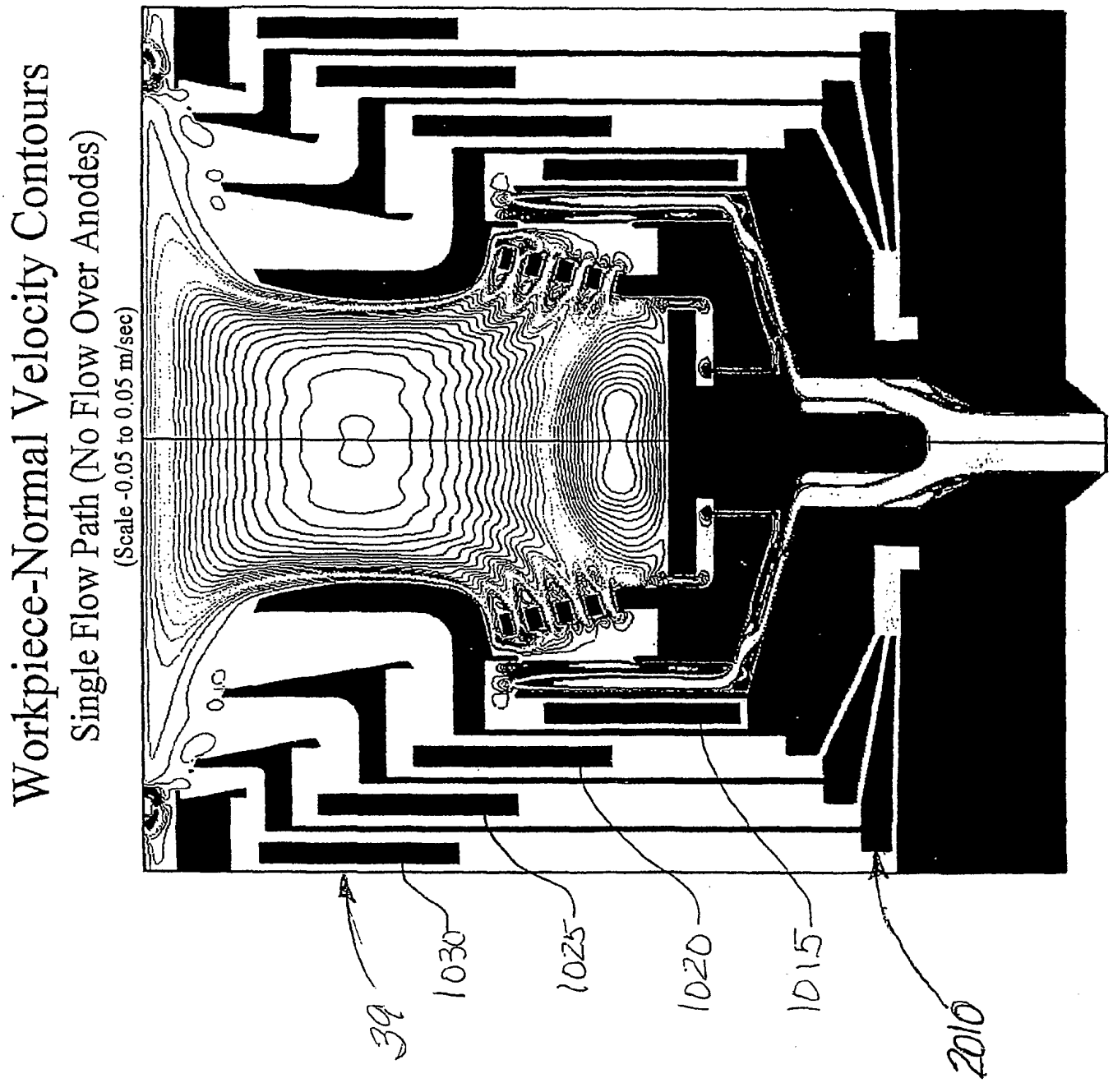
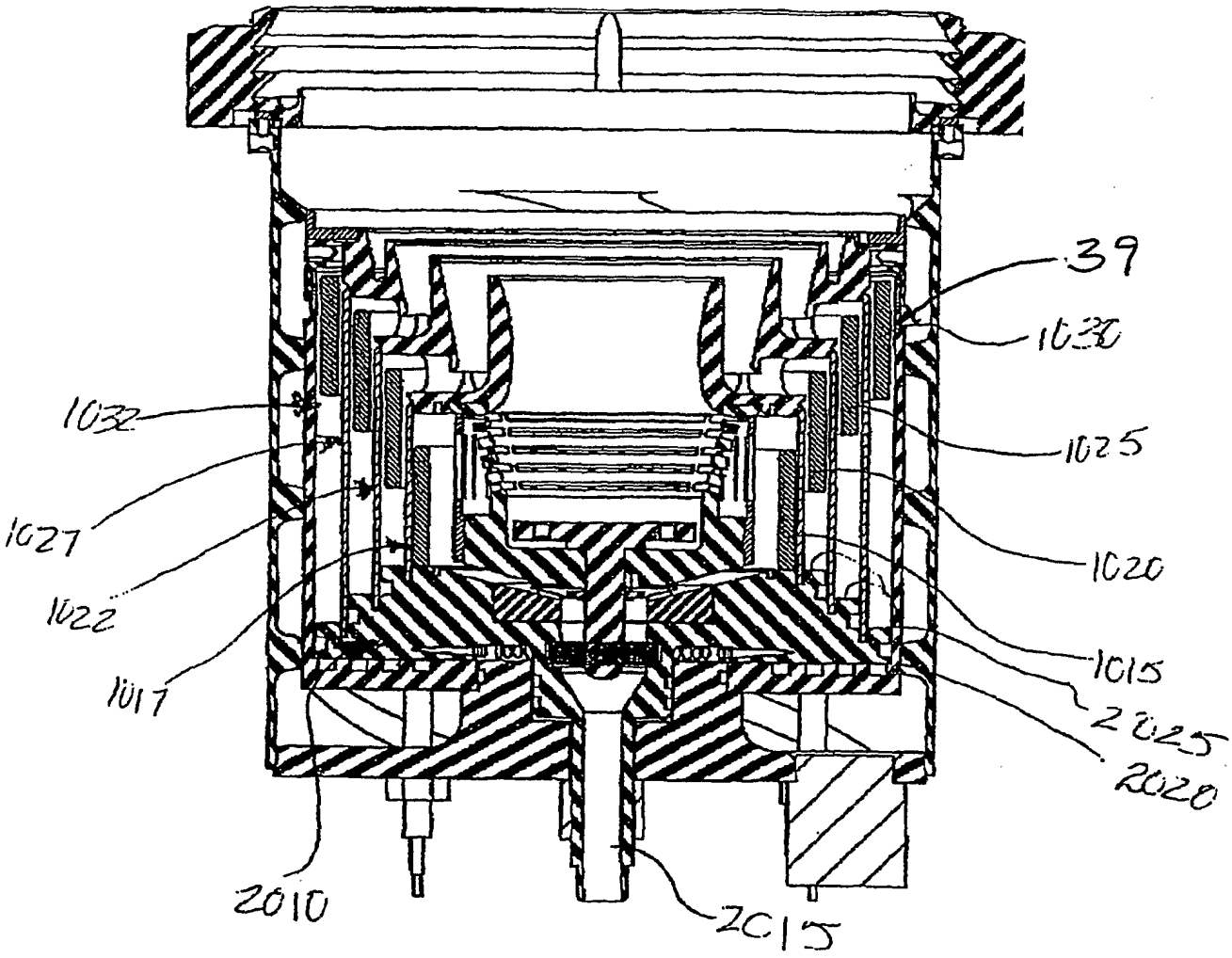

Workpiece-Normal Velocity Contours
Single Flow Path (No Flow Over Anodes)
(Scale -0.05 to 0.05 m/sec)
U
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0.0
0.0
30
1030
1025
1020
1015
2010

FIGURE 13


39
1030
1032
1025
1027
1020
1022
1015
1017
2025
2020
2010
2015

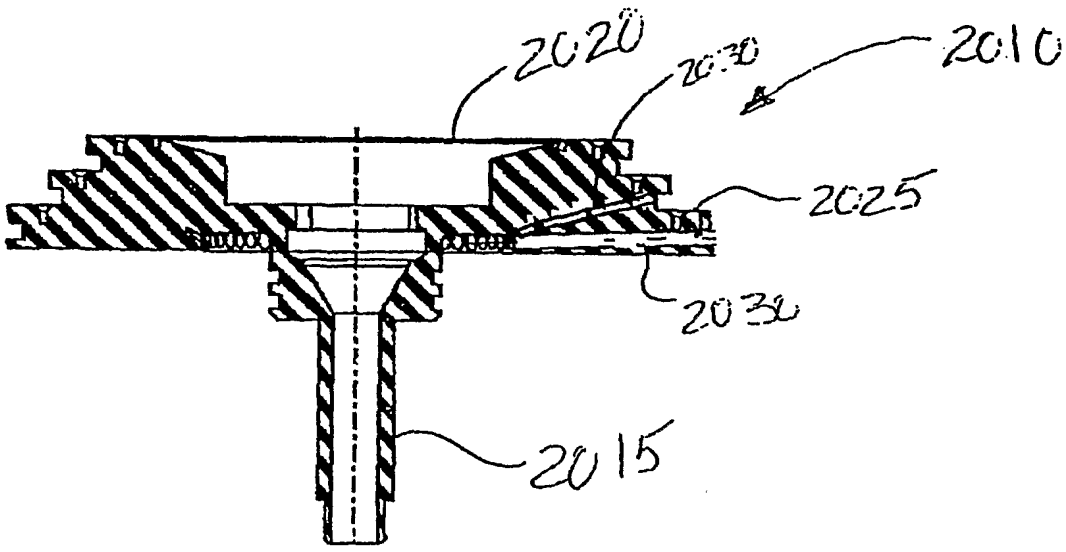
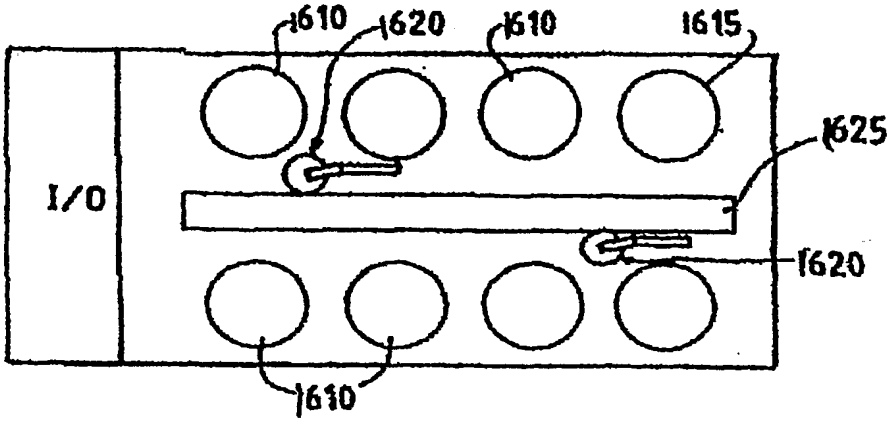


FIGURE 14

FIG. 15


1610
1620
1610
1615
1625
I/O
1620
1610

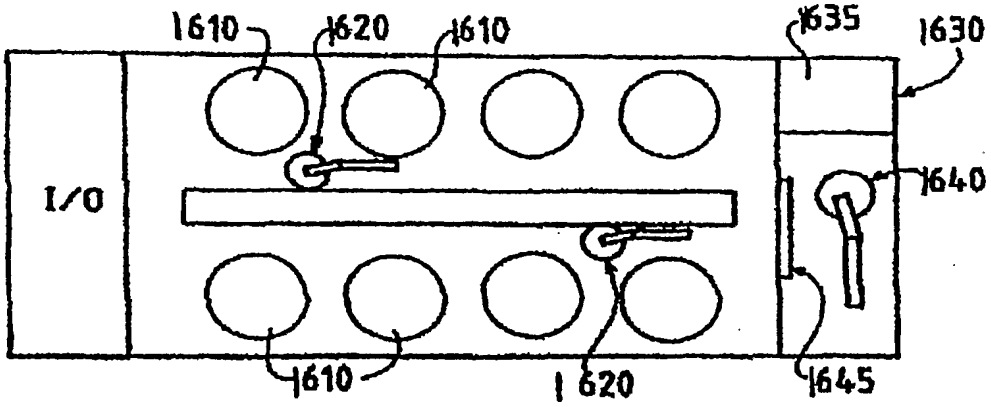

1610
1620
1610
1635
1630
1640
I/O
1610
1620
1645

FIG. 16